Nanopantography: A method for parallel writing of etched and deposited nanopatterns

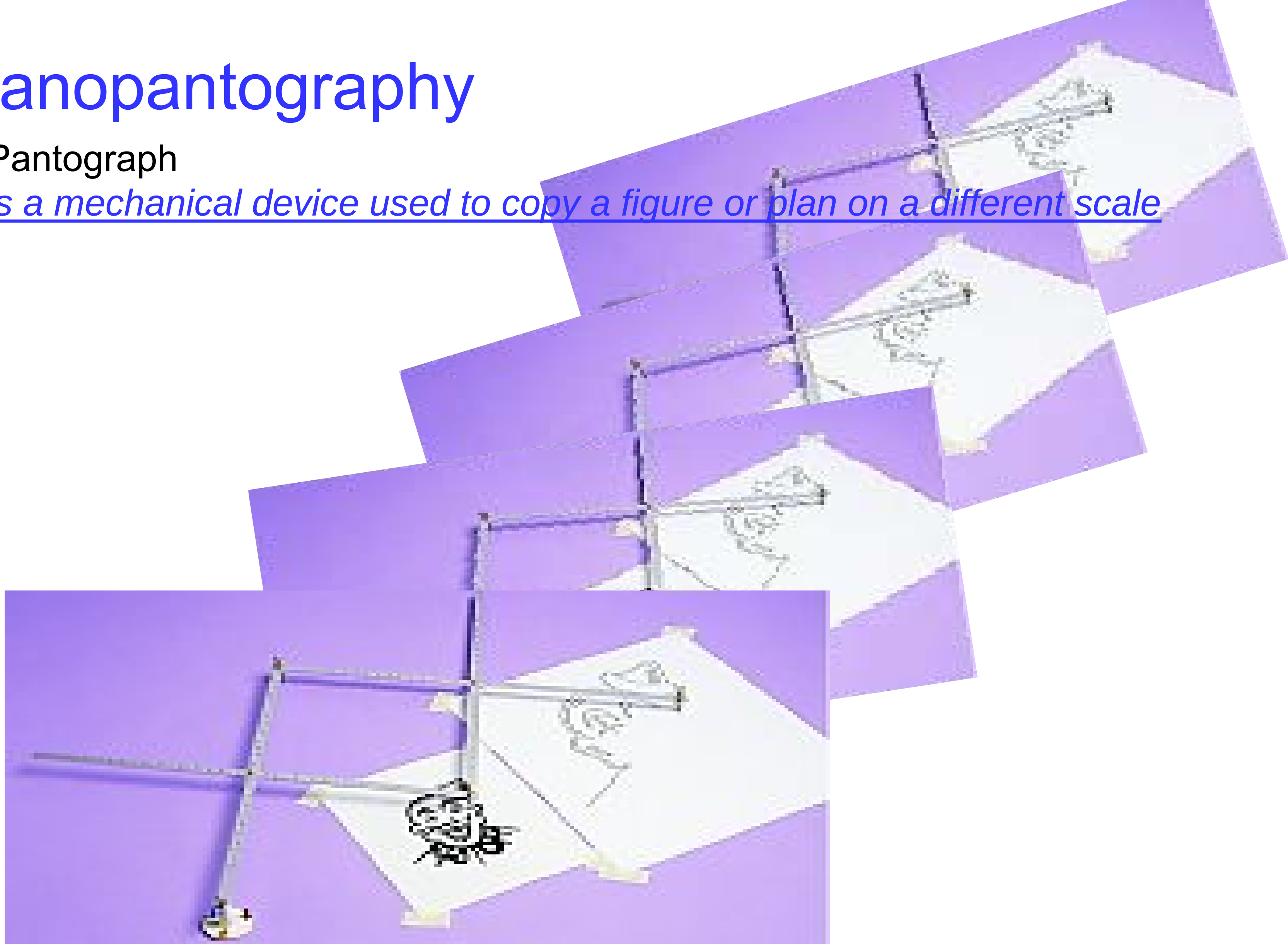
Vincent M. Donnelly[1], Lin Xu[1], Azeem Nasrullah[2], Zhiying Chen[1], Sri C. Vemula[2], Manish Jain[1], Demetre J. Economou[1] and Paul Ruchhoeft[2]

[1]Department of Chemical and Biomolecular Engineering
[2]Department of Electrical and Computer Engineering
University of Houston, Houston, TX 77204

Nanopantography

Pantograph

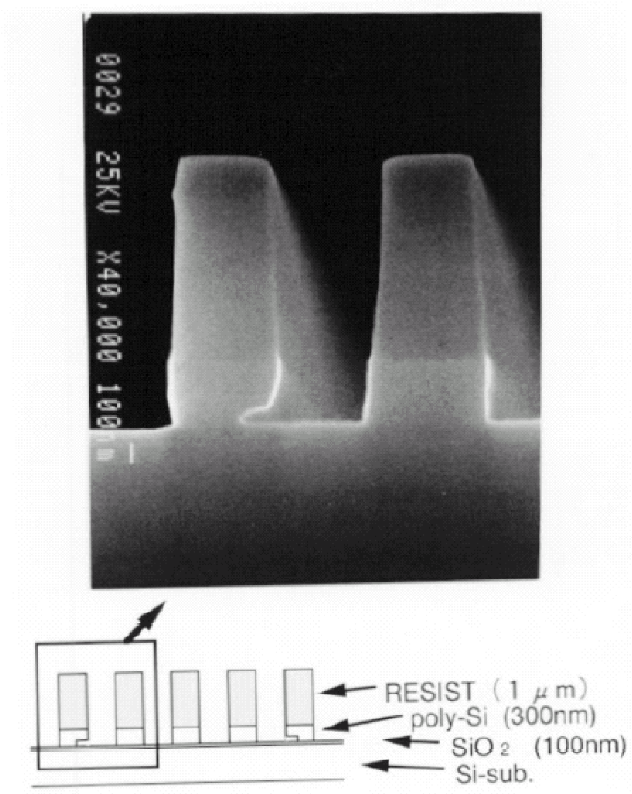
is a mechanical device used to copy a figure or plan on a different scale



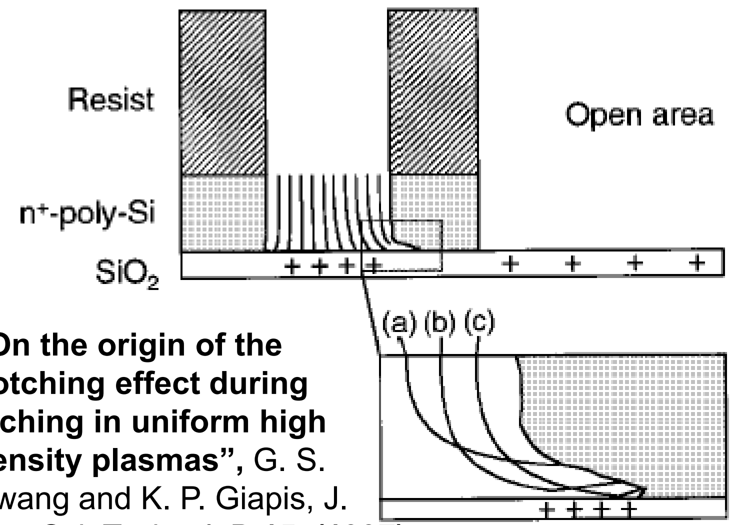
Multiscale *and* ***Parallel process***

Charge-induced "Notching" during plasma etching

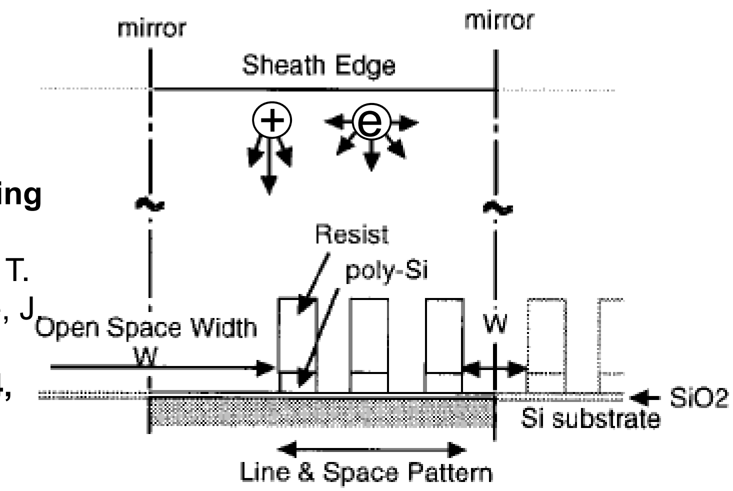
*Leads to **undesired** formation of features much smaller than the pattern size.*



"Charge accumulation effects on profile distortion in ECR plasma etching", N. Fujiwara, S. Ogino, T. Maruyama, M. Yoneda, Plasma Sources Sci. Technol. **5** (1996) 126.

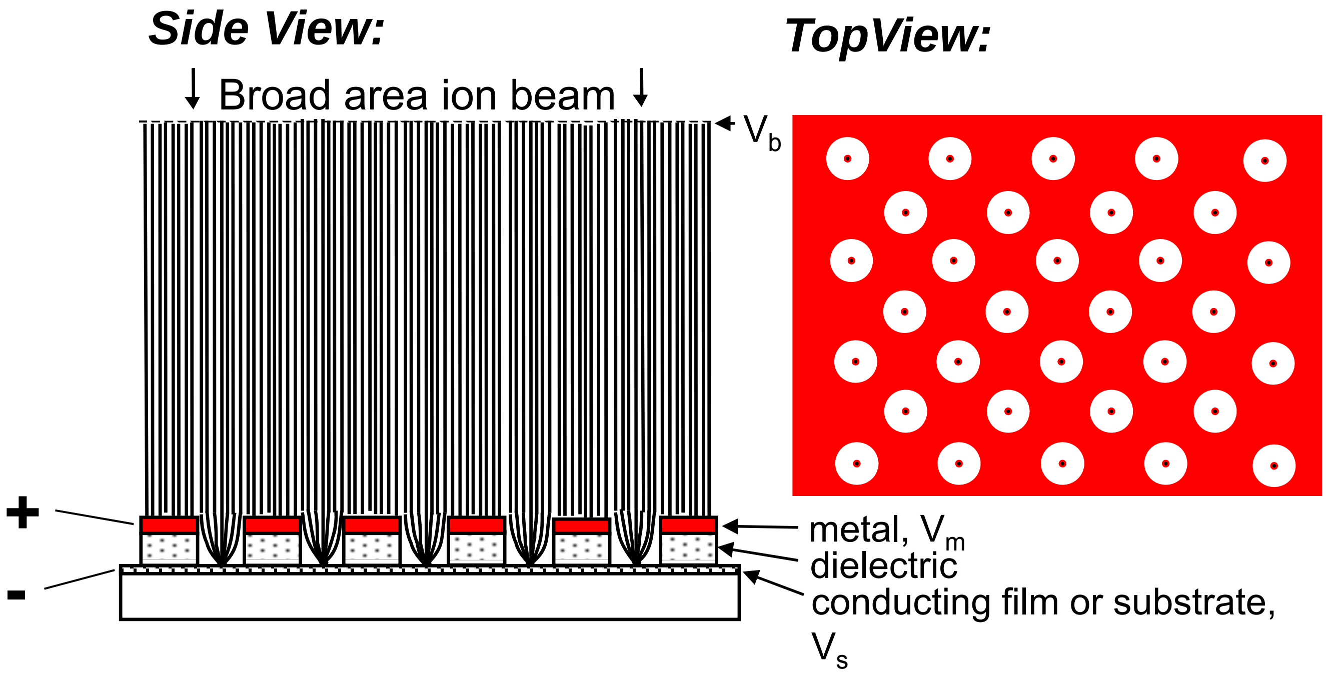


"On the origin of the notching effect during etching in uniform high density plasmas", G. S. Hwang and K. P. Giapis, J. Vac. Sci. Technol. B **15, (1997)** 70**.**



"Notching as an example of charging in uniform high density plasmas" T. Kinoshita, M. Hane, J. P. McVittie, **J. Vac. Sci. Technol. B 14, (1996),** 560.

Nanopantography



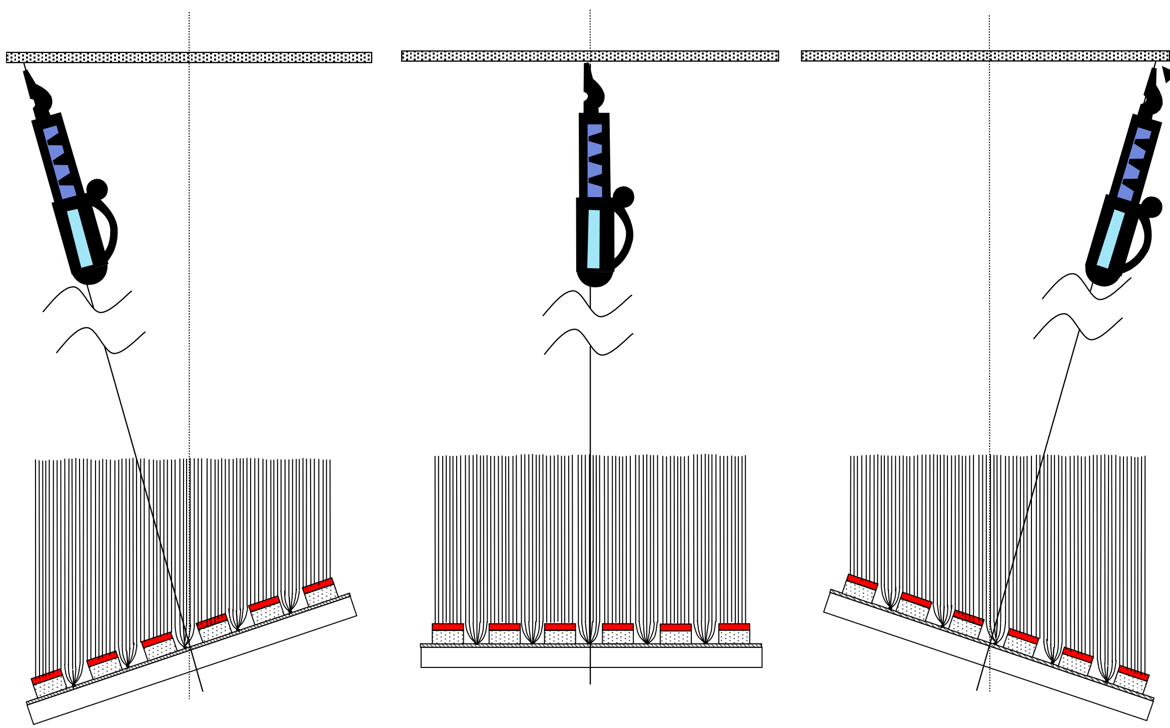
Essential components:

[*Monoenergetic ion beam*]() and [*electrostatic lens built on the wafer*]()

Capabilities and Characteristics:

- ~10nm patterning
- Self-aligned, immune to vibration and thermal expansion;
- Etching and deposition

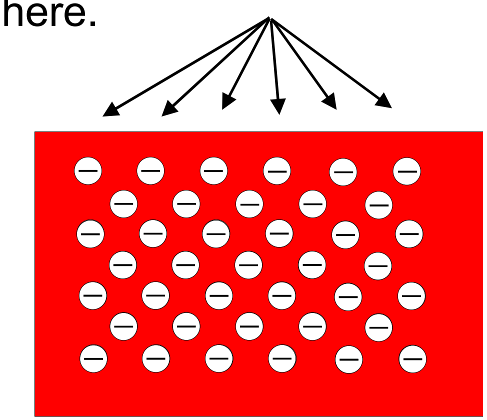
Nanopantography: Write many nanopatterns ***simultaneously*** ***by tilting the substrate***



Side view

Whatever is “written” **once** on the imaginary plane here

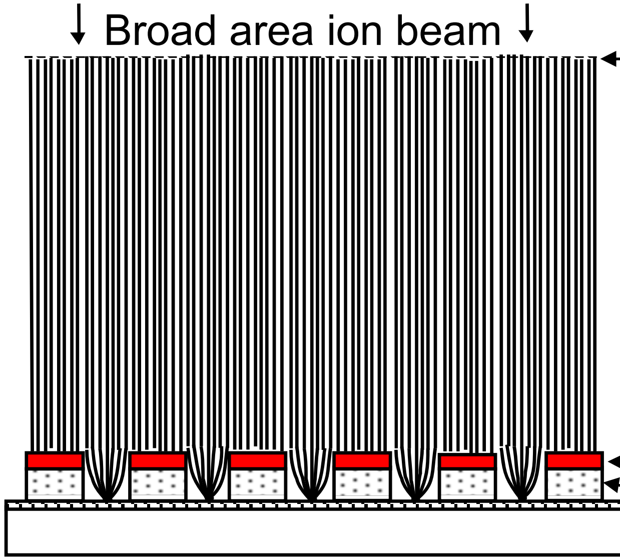
is reproduced at the bottoms of ***all*** the lenses here.



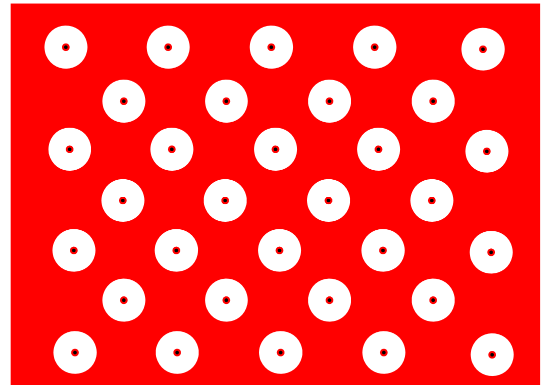
Top view

Nanopantography

Side View:



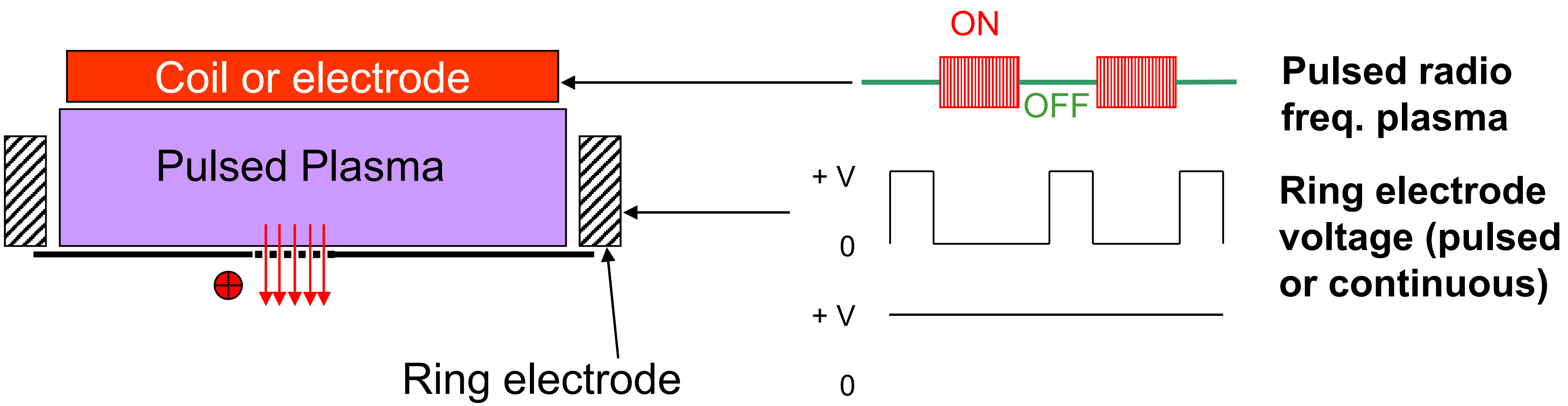
TopView:



Requires:

Monoenergetic ion beam with low divergence

Generation of monoenergetic ion beams with selectable energy

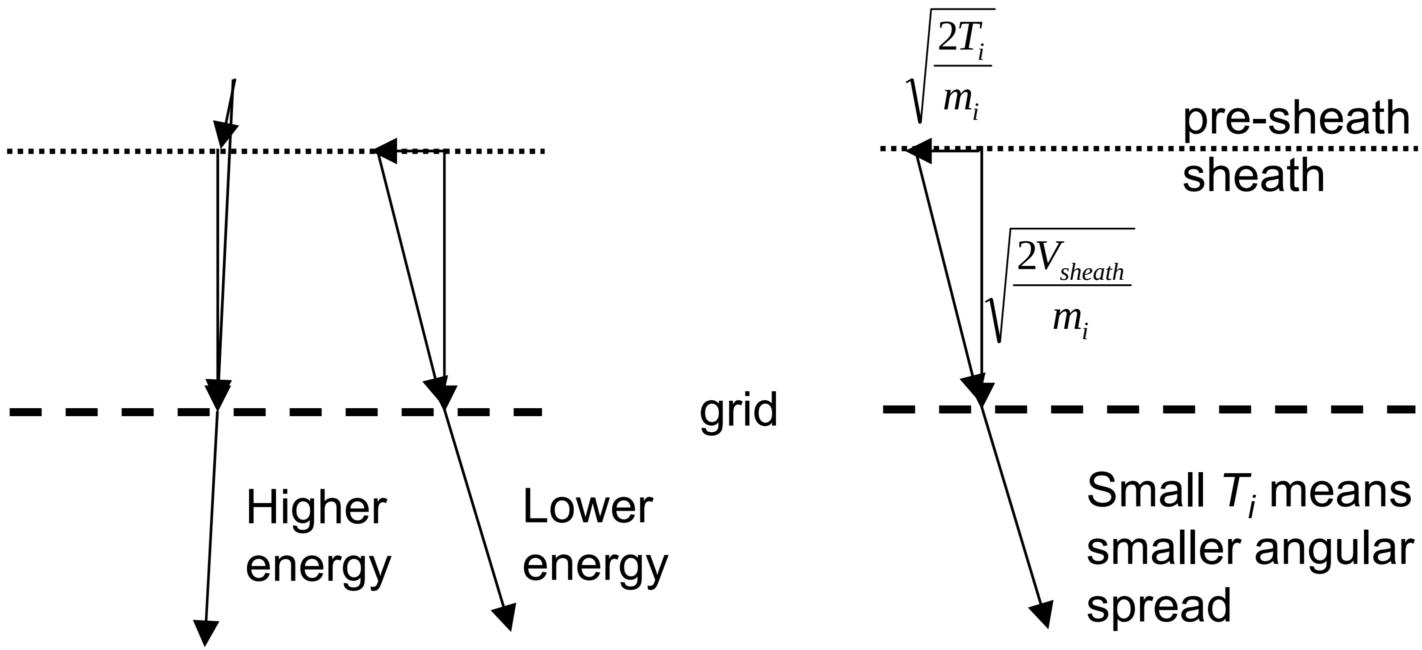


Strategy:

➢ Extracting ions at low RF plasma potential (V_p^{RF}), electron temperature (T_e) and ion temperature (T_i) in afterglow (plasma OFF) decreases the energy spread and increases the directionality of ions.

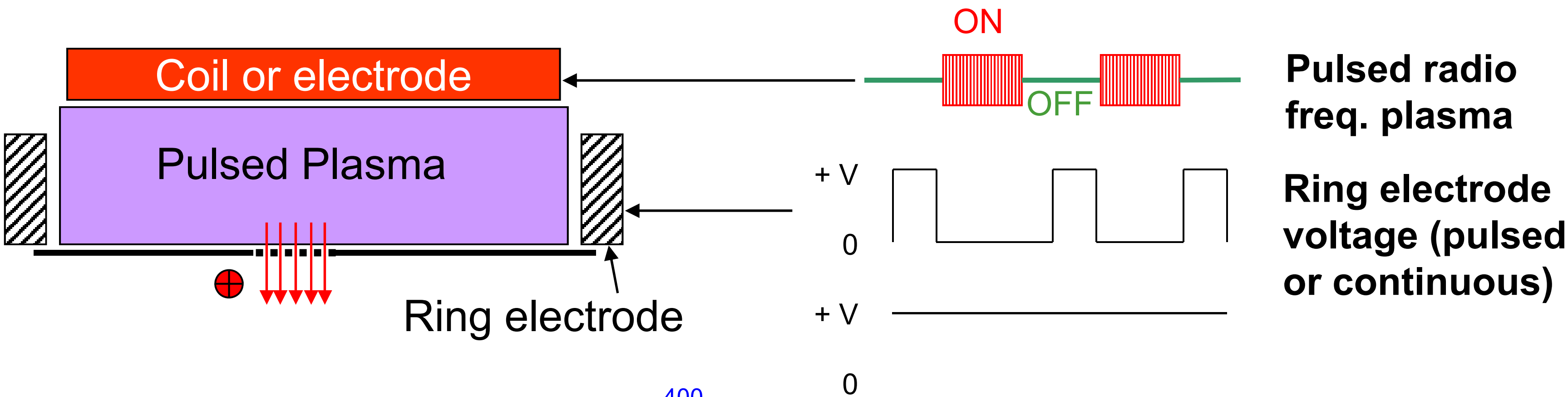
➢ Ring electrode voltage sets the desired ion beam energy.

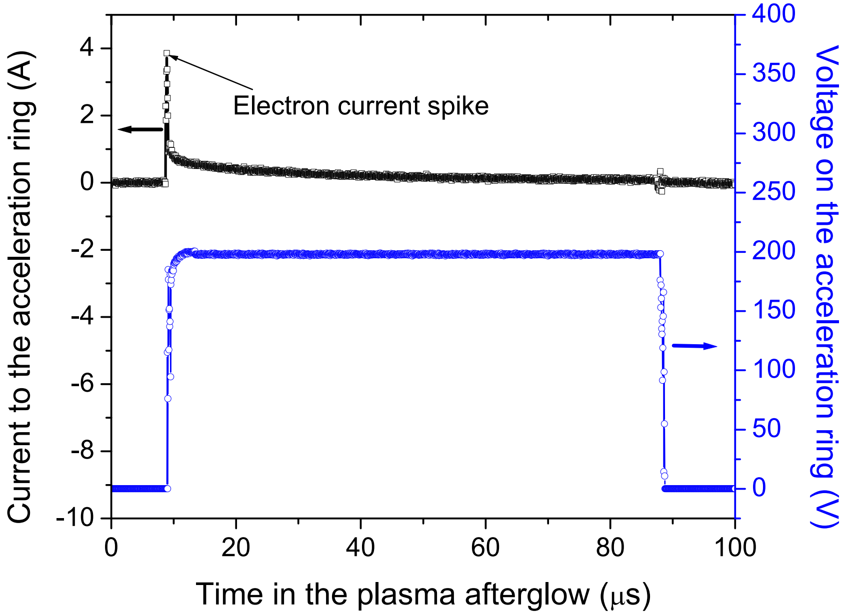
Why pulsed rf plasma for monoenergetic, reduced angular spread ion beam?



- *Ion temperature* $T_i \sim T_e / 2$
- $V_{sheath} = V_0 + V_P^{RF}$
- *Energy spread* $\propto T_i, \; , V_P^{RF}$
- $V_P^{RF} = 0$ and T_i is lowered by turning plasma off

Time-resolved electron current in response to a 200 V pulse applied in the afterglow of an inductively-coupled pulsed plasma



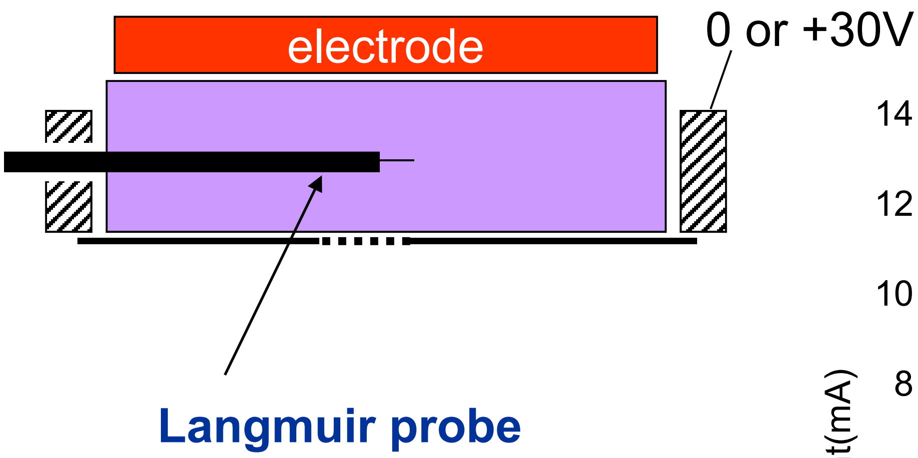


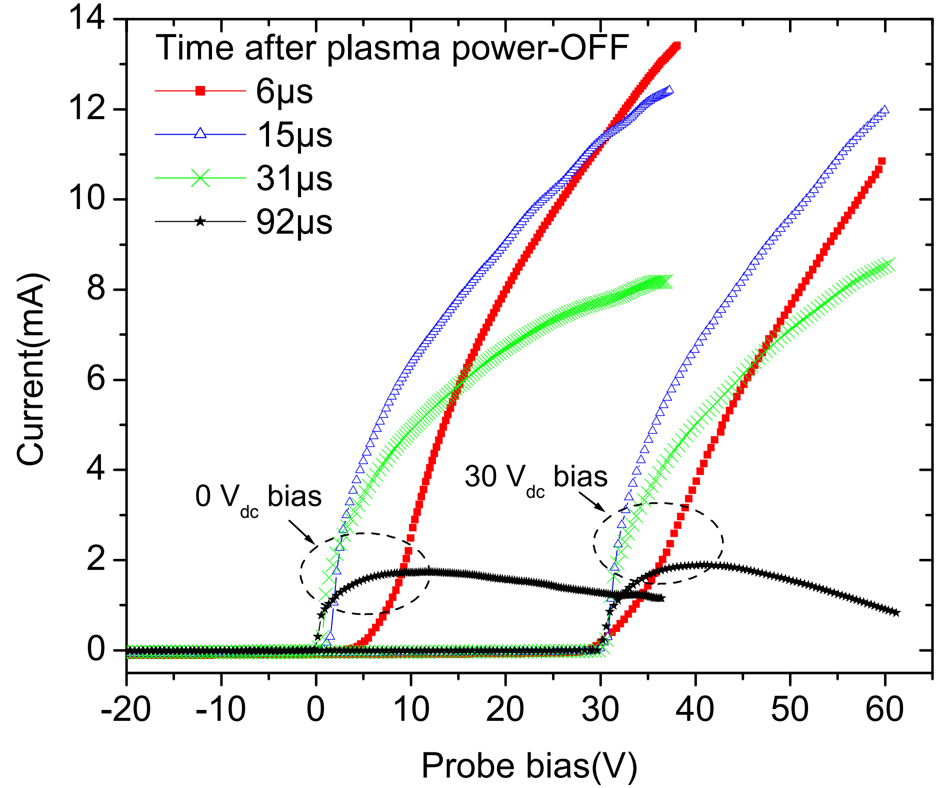
8 mTorr, 5 KHz modulation frequency, 50% duty cycle, 100 W average RF power on the internal coil, no power on the target electrode

Time-resolved Langmuir probe I-V characteristics in the afterglow of a pulsed plasma

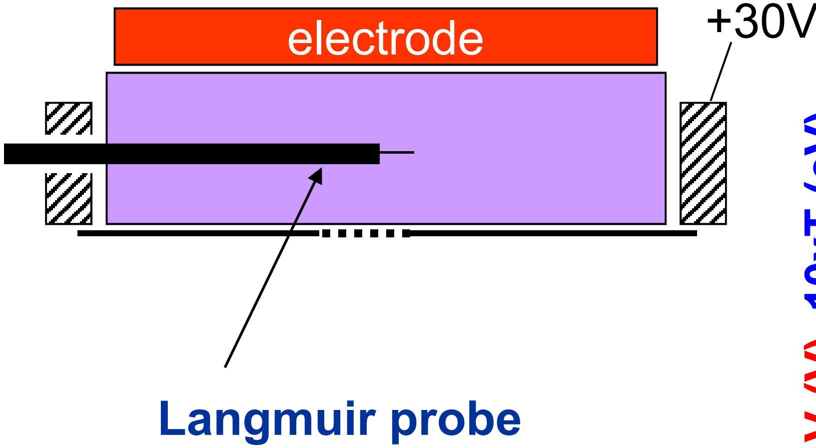
0 or +30V DC bias applied on the acceleration ring

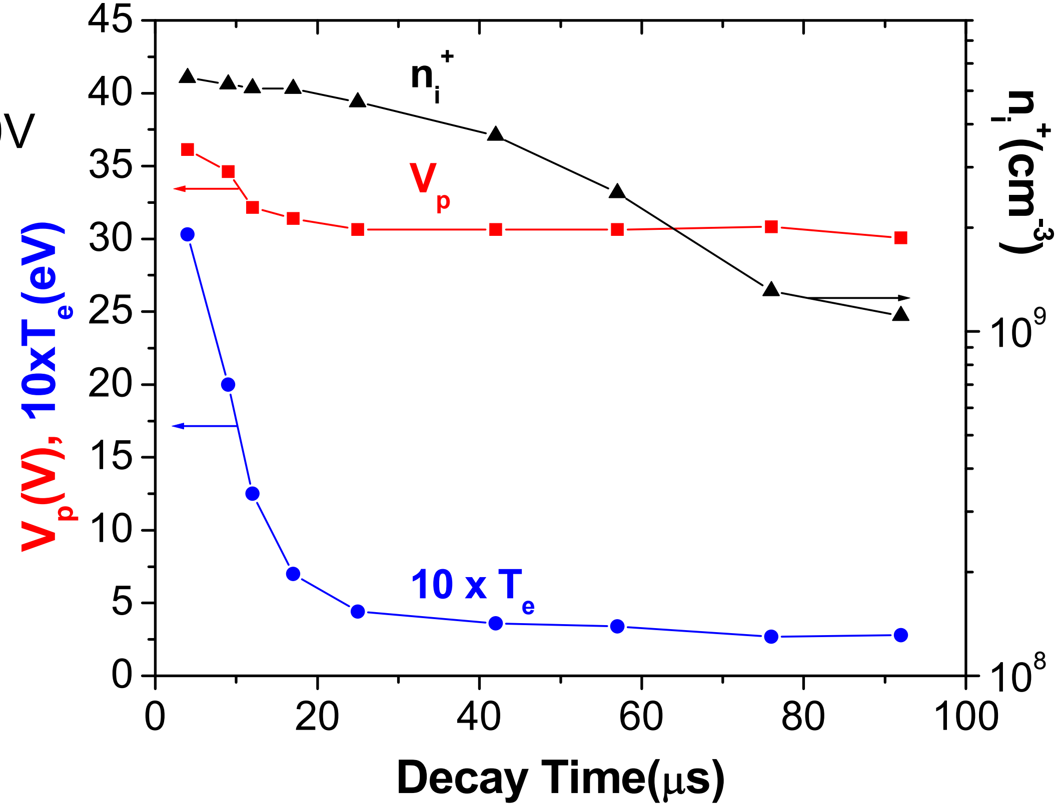
(15.9 mTorr, 5 KHz modulation frequency, 50% duty cycle, 30 W average RF power on the target electrode).





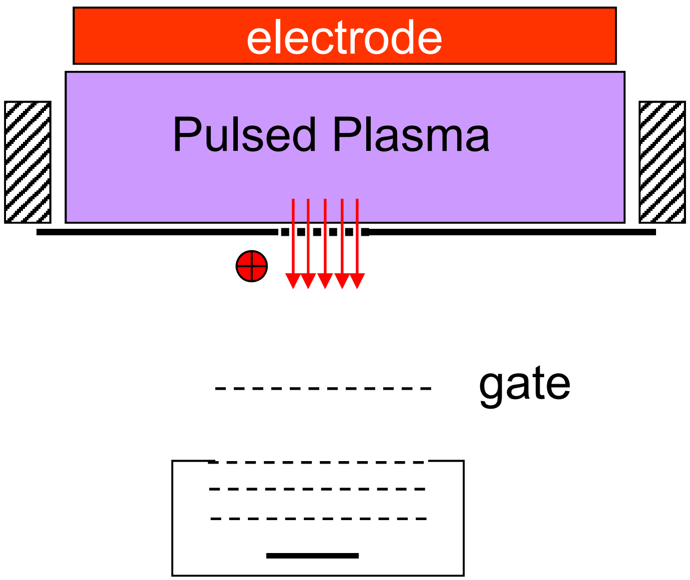
Langmuir probe measurement of evolution of plasma potential (V_p), electron temperature (T_e) and positive ion density (n_i^+) in the afterglow



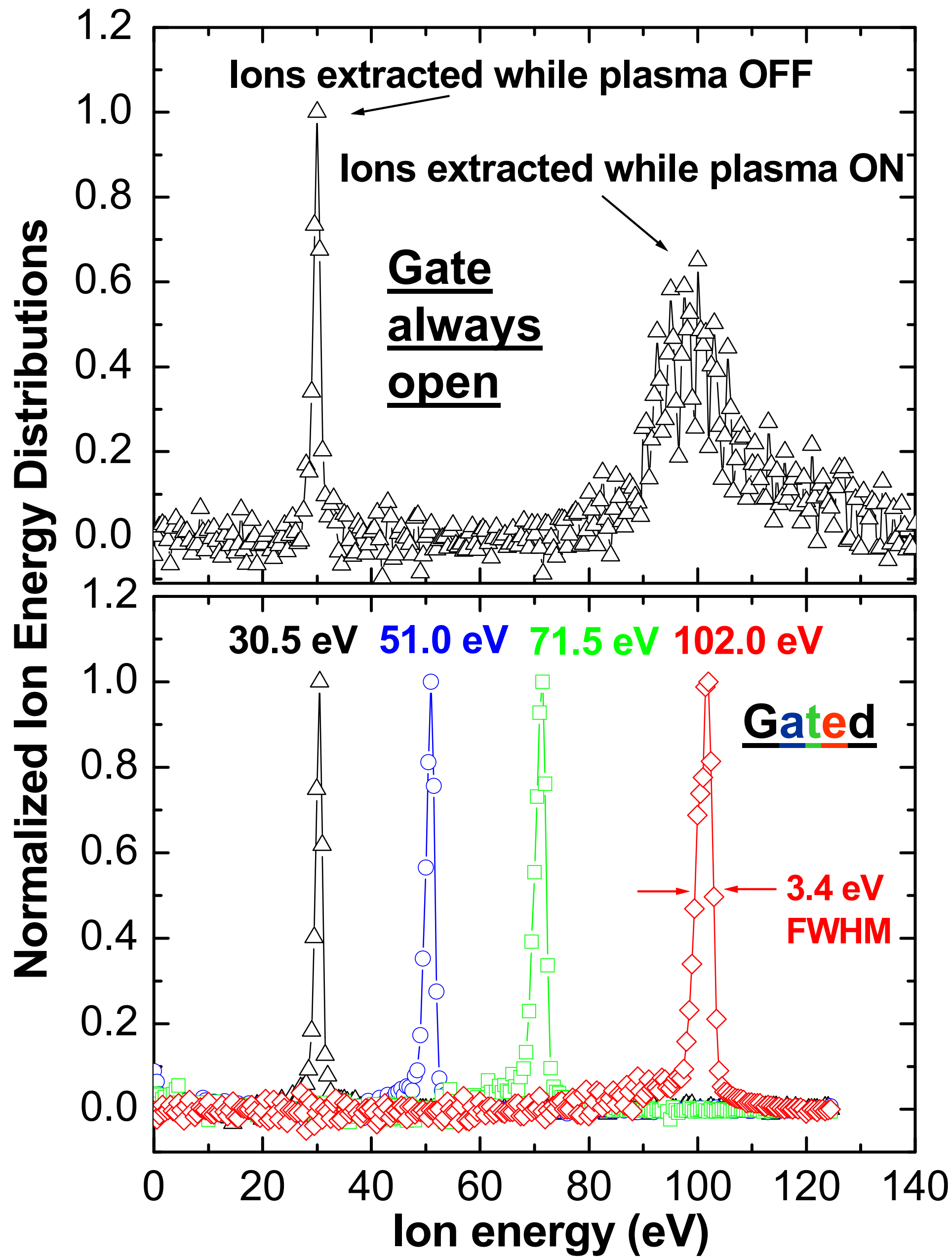


- 16 mTorr Ar plasma, 13 MHz, capacitively-coupled plasma (CCP), 5 KHz modulation frequency, 50% duty cycle).
- +30V continuous bias on the ring electrode.

Nearly monoenergetic Ar^+ beam extracted from a pulsed Ar CCP, continuous DC ring electrode voltage



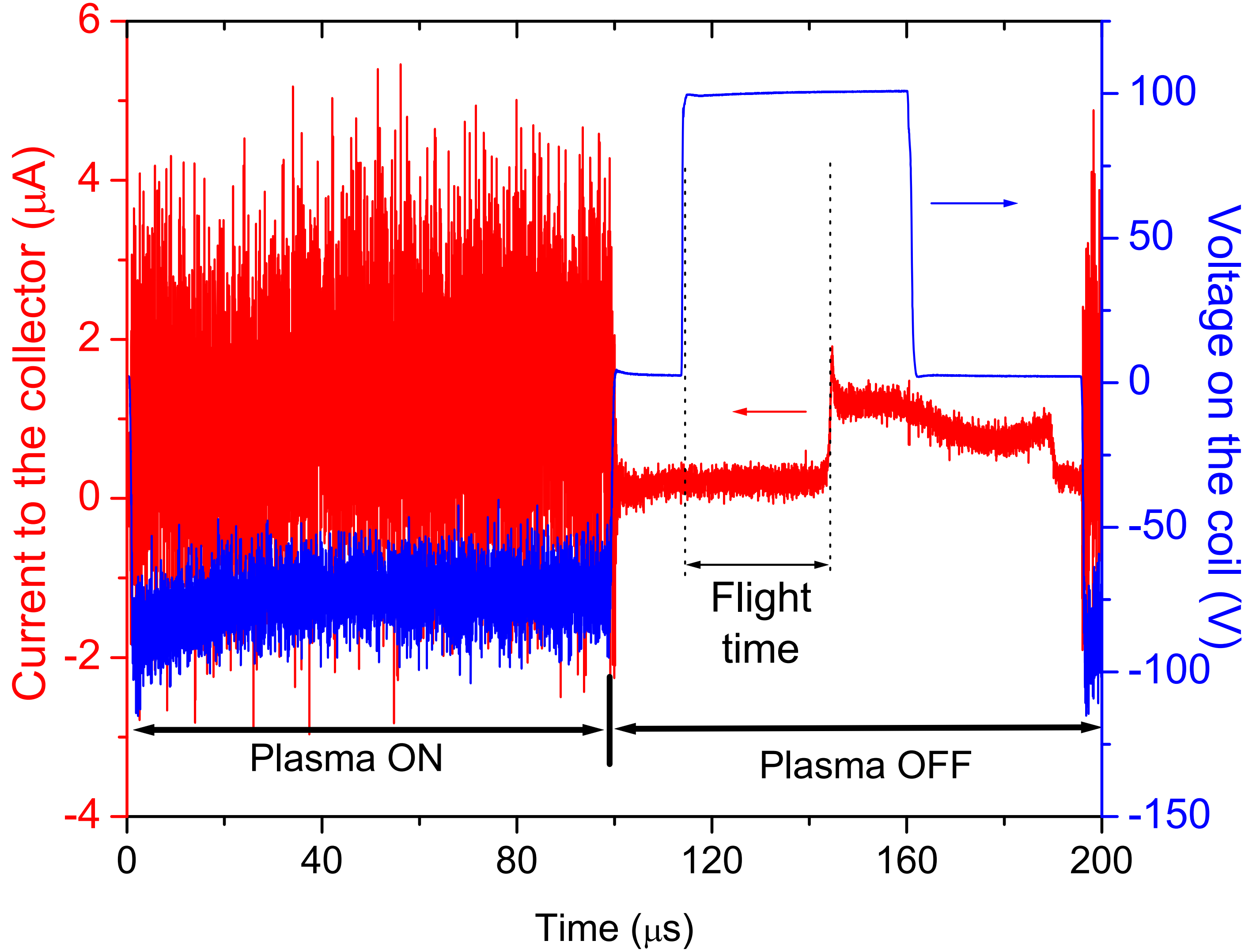
Retarding field ion energy analyzer
resolution ≈ 3%



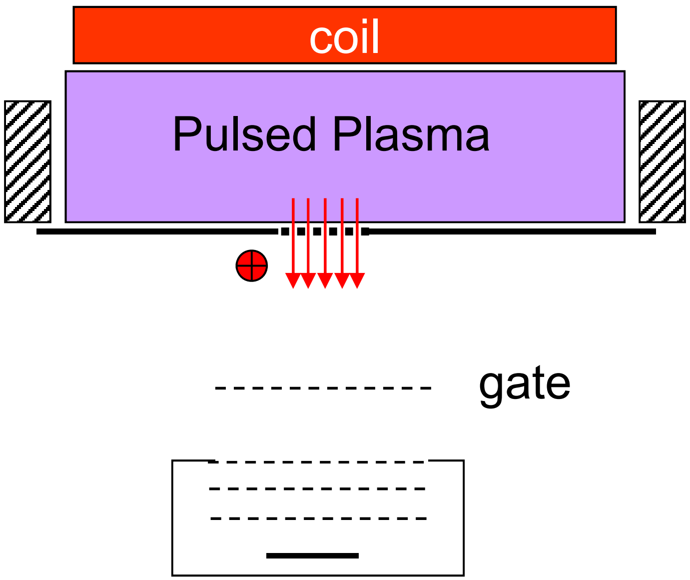
L. Xu, D. J. Economou, V. M. Donnelly, P. Ruchhoeft, *Appl. Phys. Lett.* **87**, 041502 (2005).

Time-resolved ion current downstream from the plasma

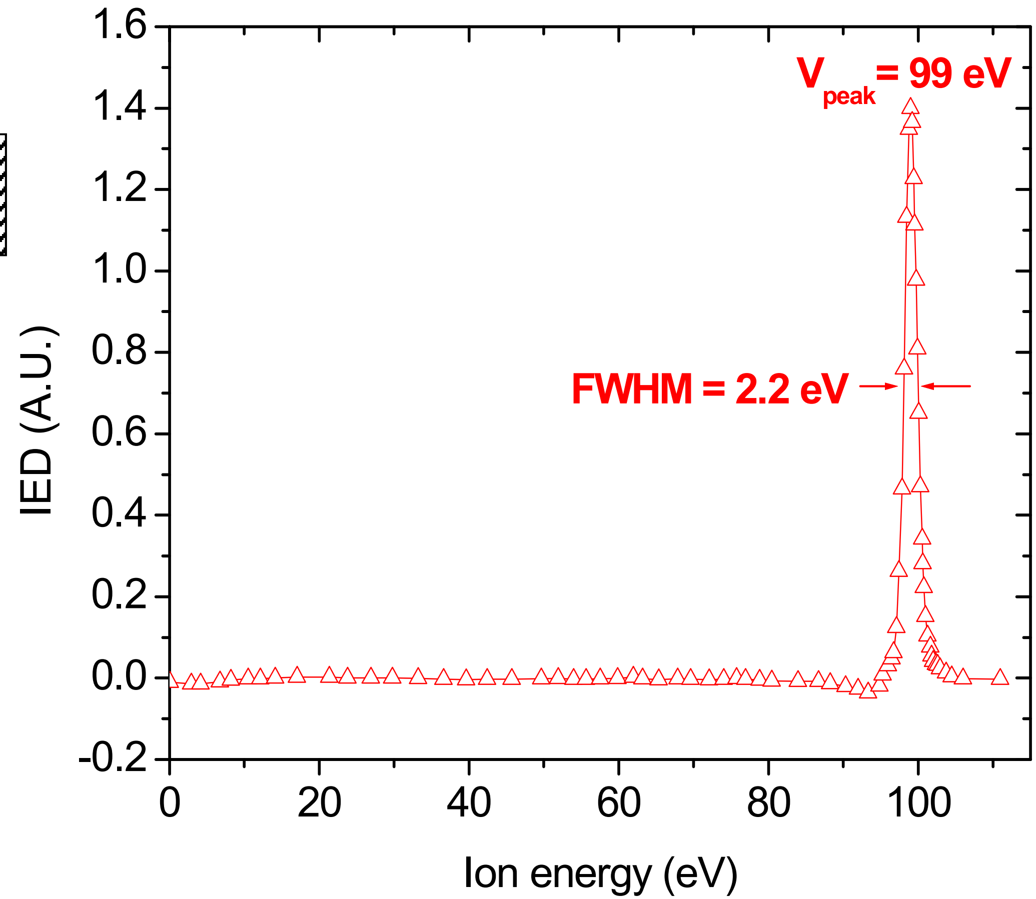
- Ion current on a 3”-dia. collector, 60 cm downstream of the plasma source.
- 100 V acceleration ring pulsed between 14 μs and 61 μs into the afterglow.
- 8 mTorr, 5 KHz modulation frequency, 50% duty cycle, 100 W average coil power.



Nearly monoenergetic Ar^+ beam extracted from a pulsed Ar Inductively coupled plasma (ICP)



Retarding field ion energy analyzer
resolution ≈ 2%



Si nano-etching

Ar ion beamlets and Cl_2 gas

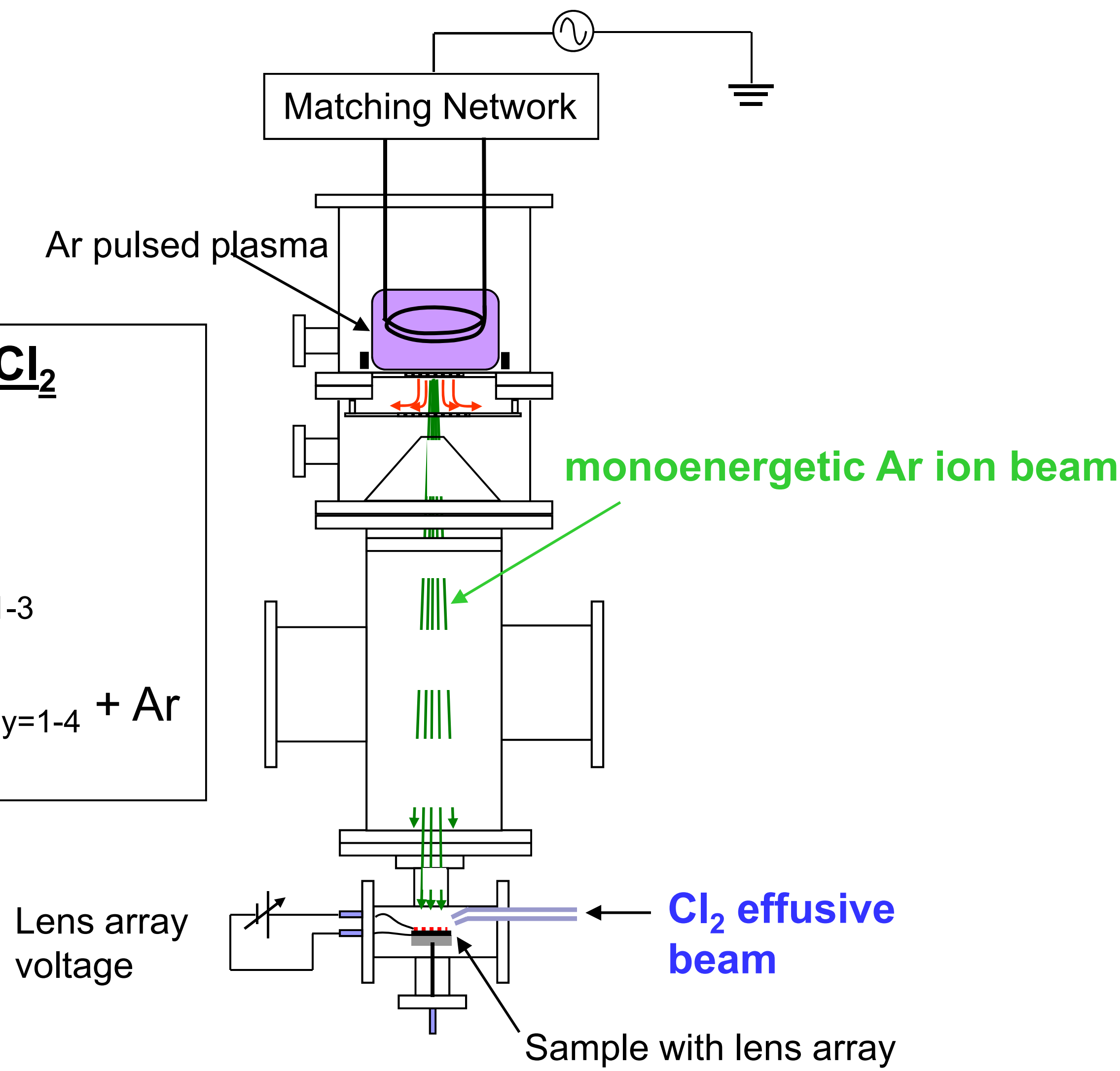
Nanopantography for Ar^+-assisted etching of Si by Cl_2

Ar^+-assisted etching by Cl_2

$Cl_{2(g)} + 2Si \rightarrow 2Si\text{-}Cl_{(ads)}$

$xSi\text{-}Cl_{(ads)} \rightarrow SiCl_{x(ads),\ x=1\text{-}3}$

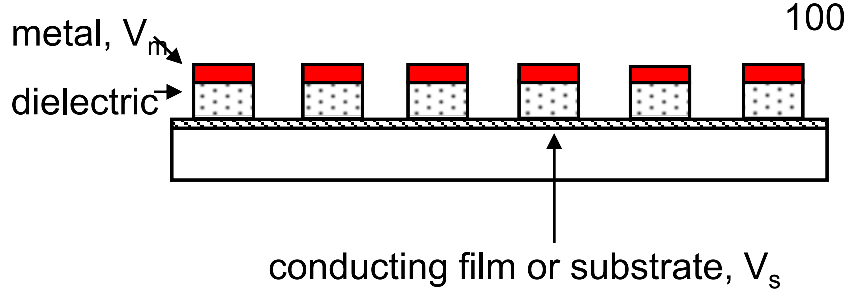
$Ar^+ + SiCl_{x(ads)} \rightarrow SiCl_{y(g),\ y=1\text{-}4} + Ar$



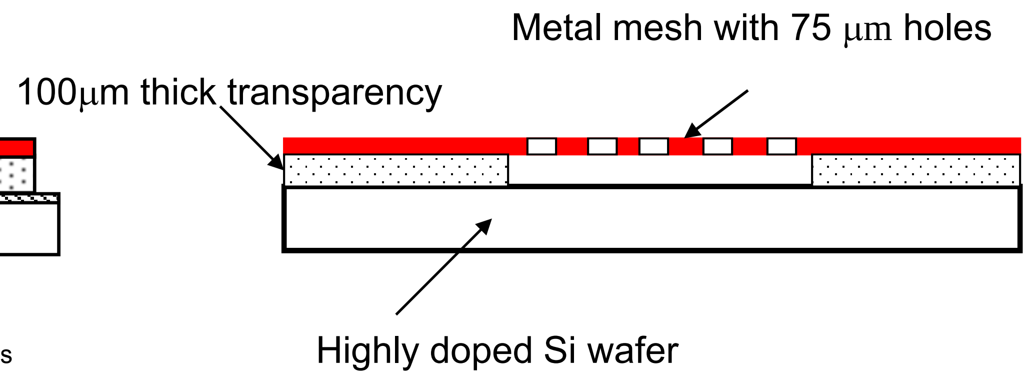
Proof of Principle (PoP) Experiment:

Focusing depends on
aspect ratio of lens structure and *potential across the dielectric material*

Nano version: **Nanopantography**



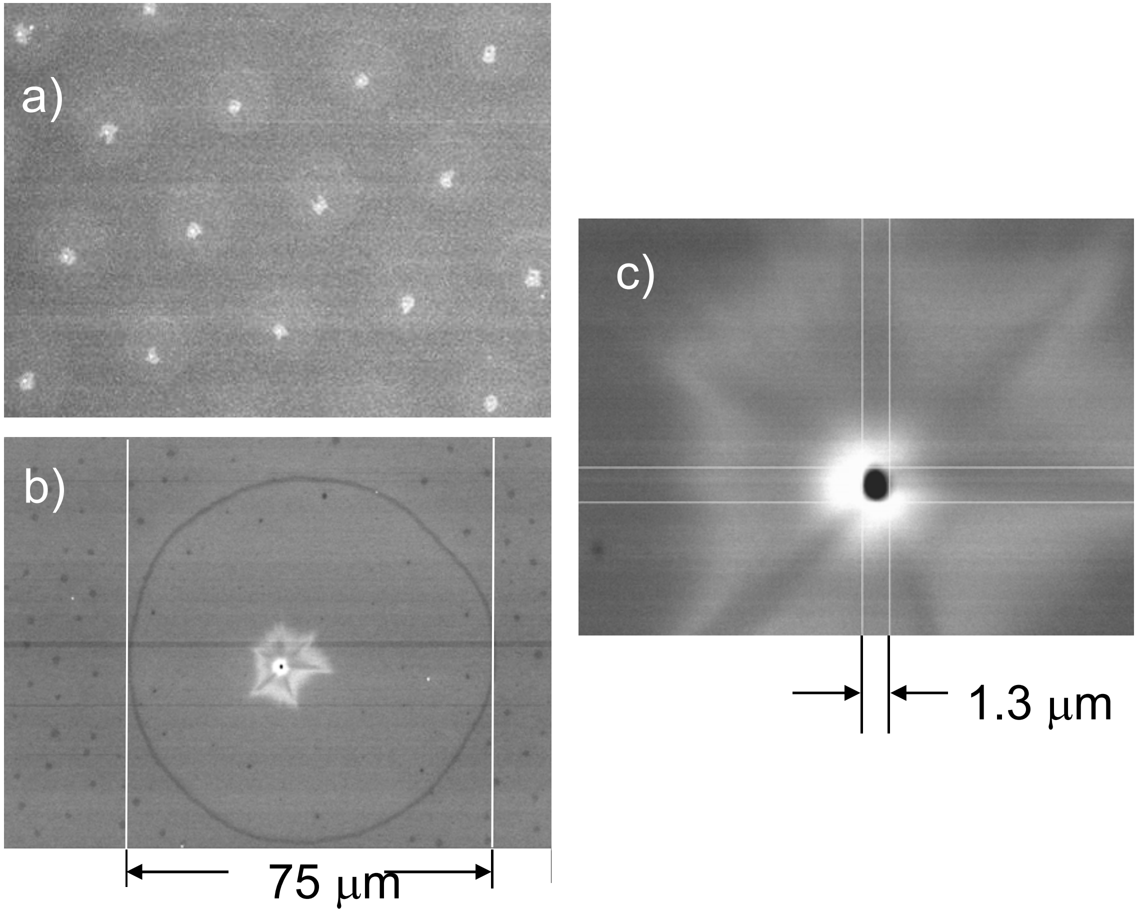
Micron version: **PoP Experiment**



PoP Experiment:

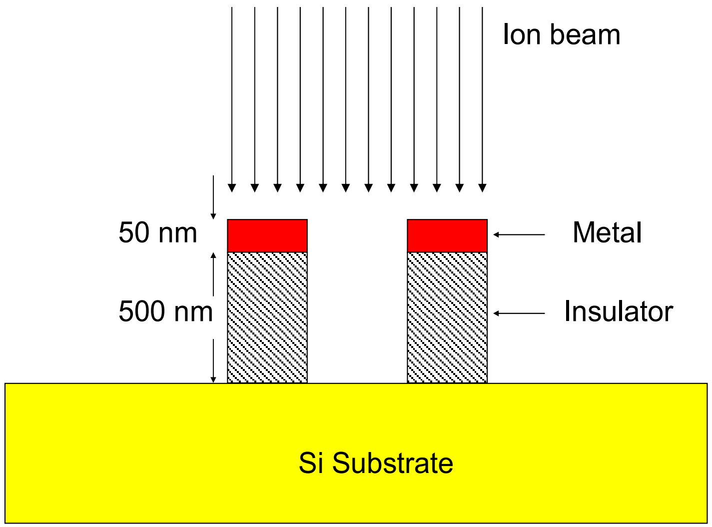
- *Prove the principle and characterize the quality of ion beam*
- *Easy to analyze the sample*

SEM picture of PoP experiment after Ar+ etching



- The etched hole size is around ***1.3 µm***, resulting in a reduction factor of ~***60x***
- From AFM measurement, the hole is around ***1 µm*** deep.

Micro-Einzel Lenses: Simulations



Solve Laplace eq. in cyl. Coord.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V}{\partial r}\right)+\frac{\partial^2 V}{\partial z^2}=0.$$

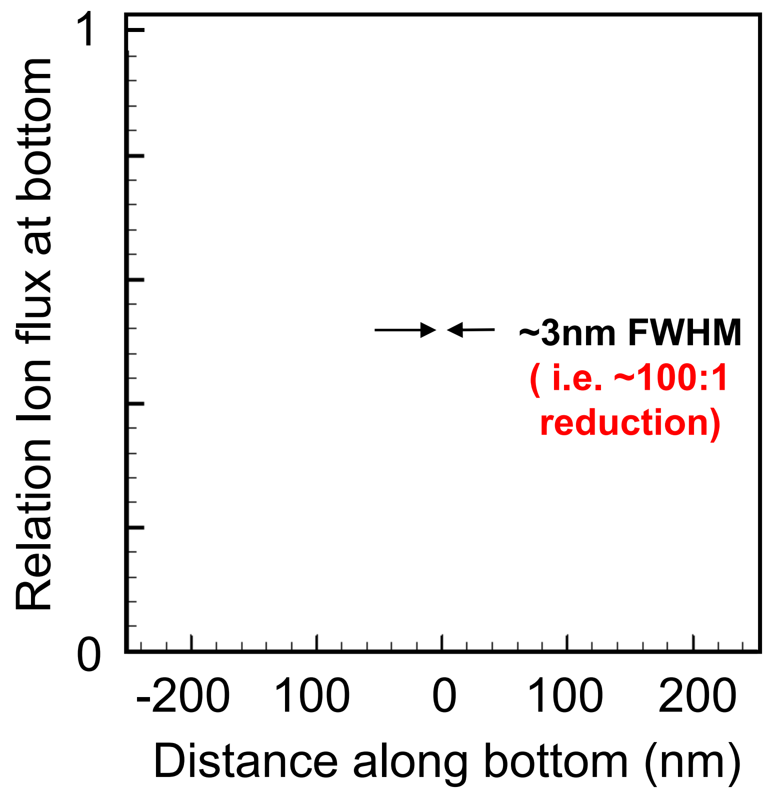
Find electric field

$$E = -\nabla V$$

Integrate eqs. of motion for

$$\frac{du_r}{dt}=\frac{e}{m}E_r,\ \frac{du_z}{dt}=\frac{e}{m}E_z$$

Simulation for 260 nm dia. lens



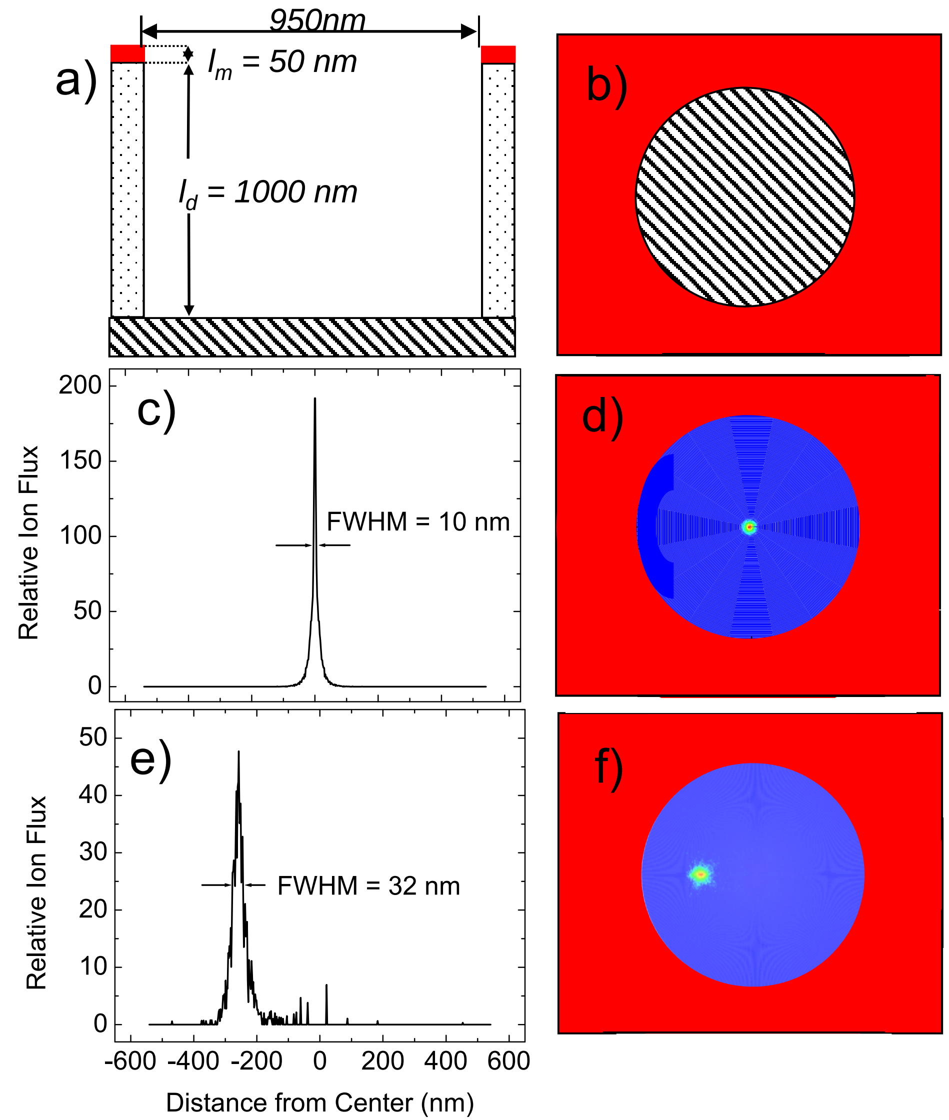
Fine focusing requires:

1. Narrow energy spread, $\Delta E \leq \sim 2\text{eV}$
2. Narrow angular spread, $\Delta\theta \leq 1^{\circ}$

Nanopantography Simulations

Lens structure

Conductor / dielectric / conductor



At normal incidence

Vm=197.2V, Vs=100V

Tilted by 30 °

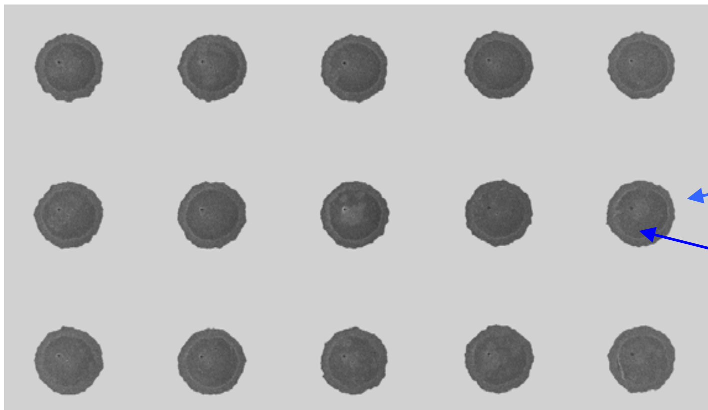
Vm=196.7V, Vs=100V

Nanopantography results: Ar^{+}-assisted etching of Si by Cl_2

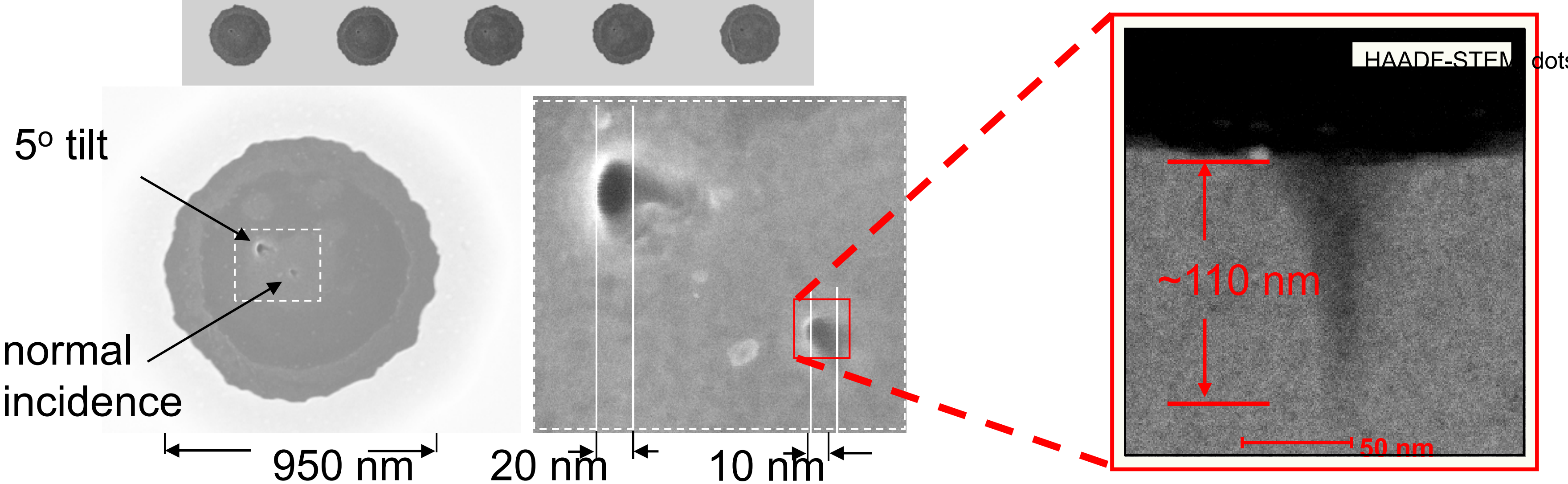
Top view of lens array

SEM

L. Xu et al. ***Nano Letters, 5, 2563 (2005).***



TEM

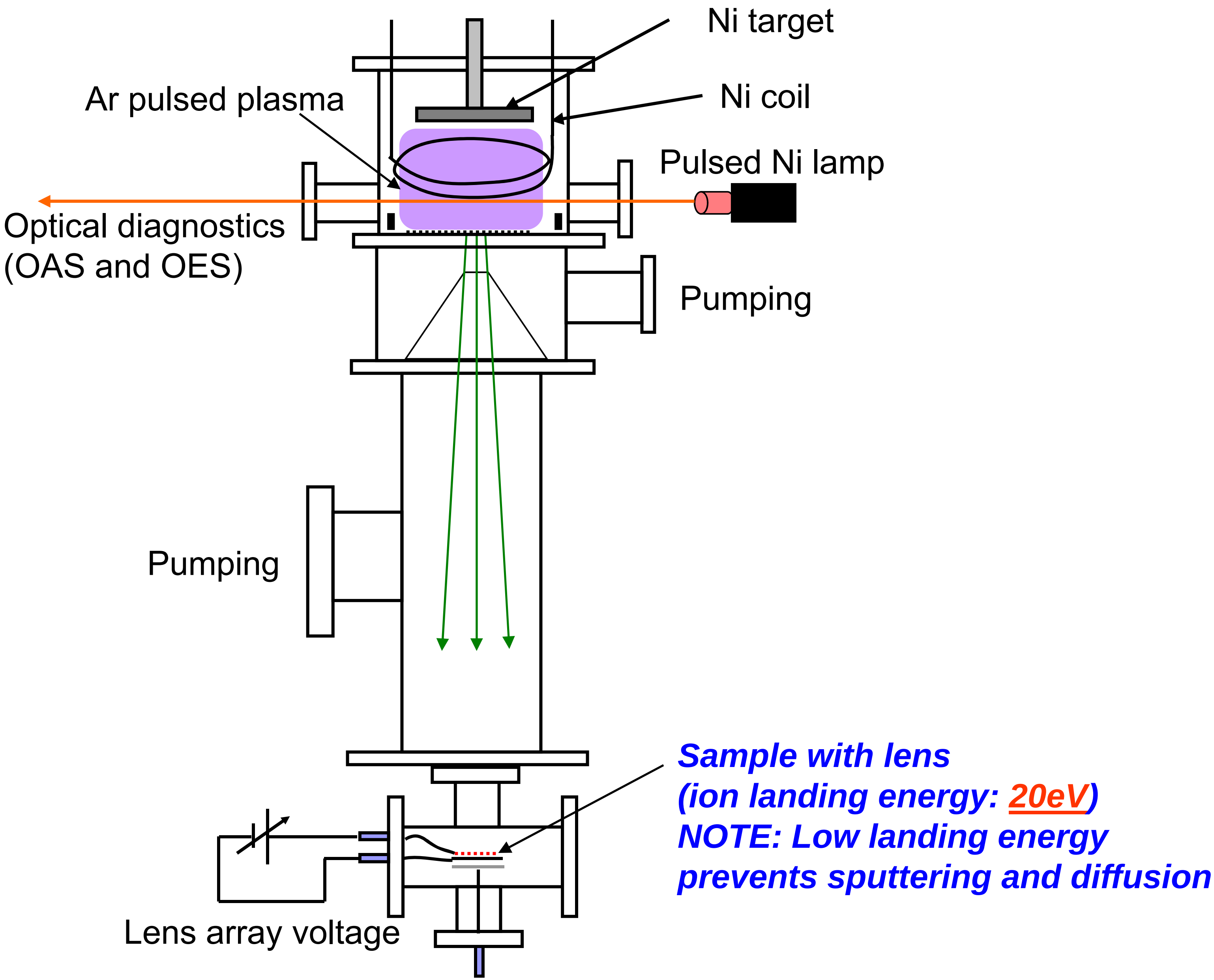


- ***Size reduction factor of ~95X***
- ***Focused point can be displaced along the substrate surface***

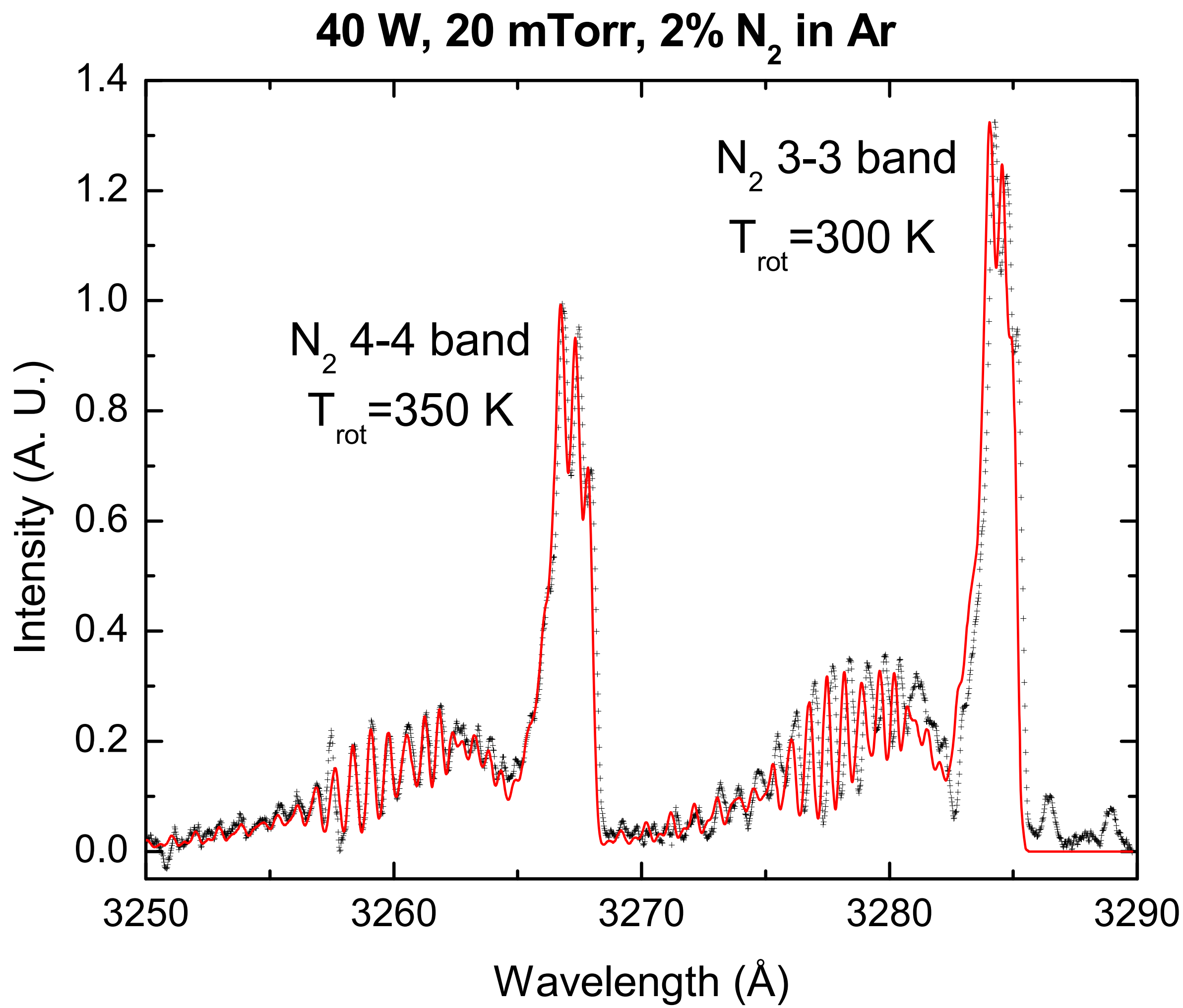
Ni nano-dot deposition

Low energy Ni ion beamlets

Nanopantography results: Ni nanodot deposition

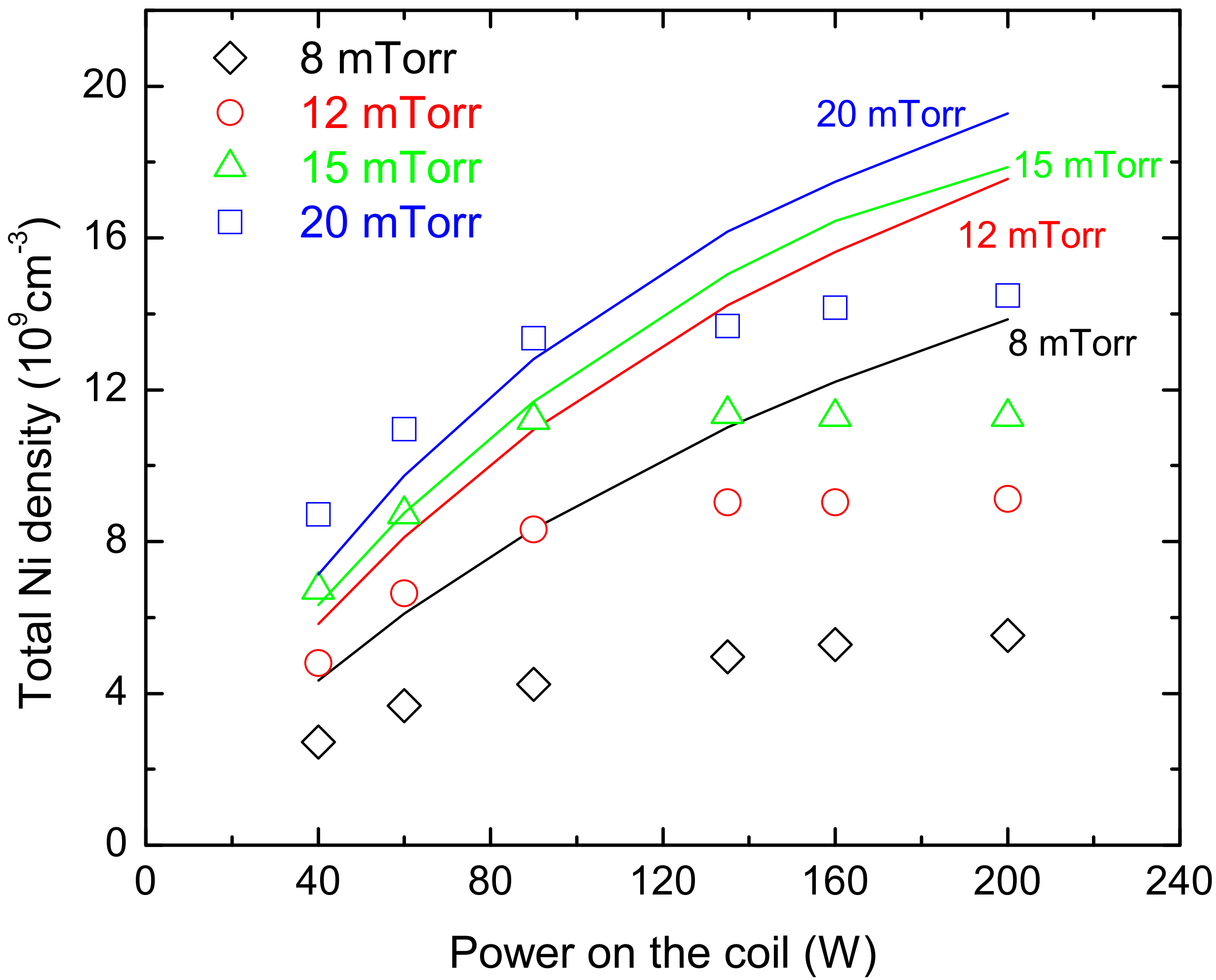


Plasma Neutral Gas Temperature Measured by Trace $N_2(C^3\Pi_u$- $B^3\Pi_g)$ Emission Spectroscopy



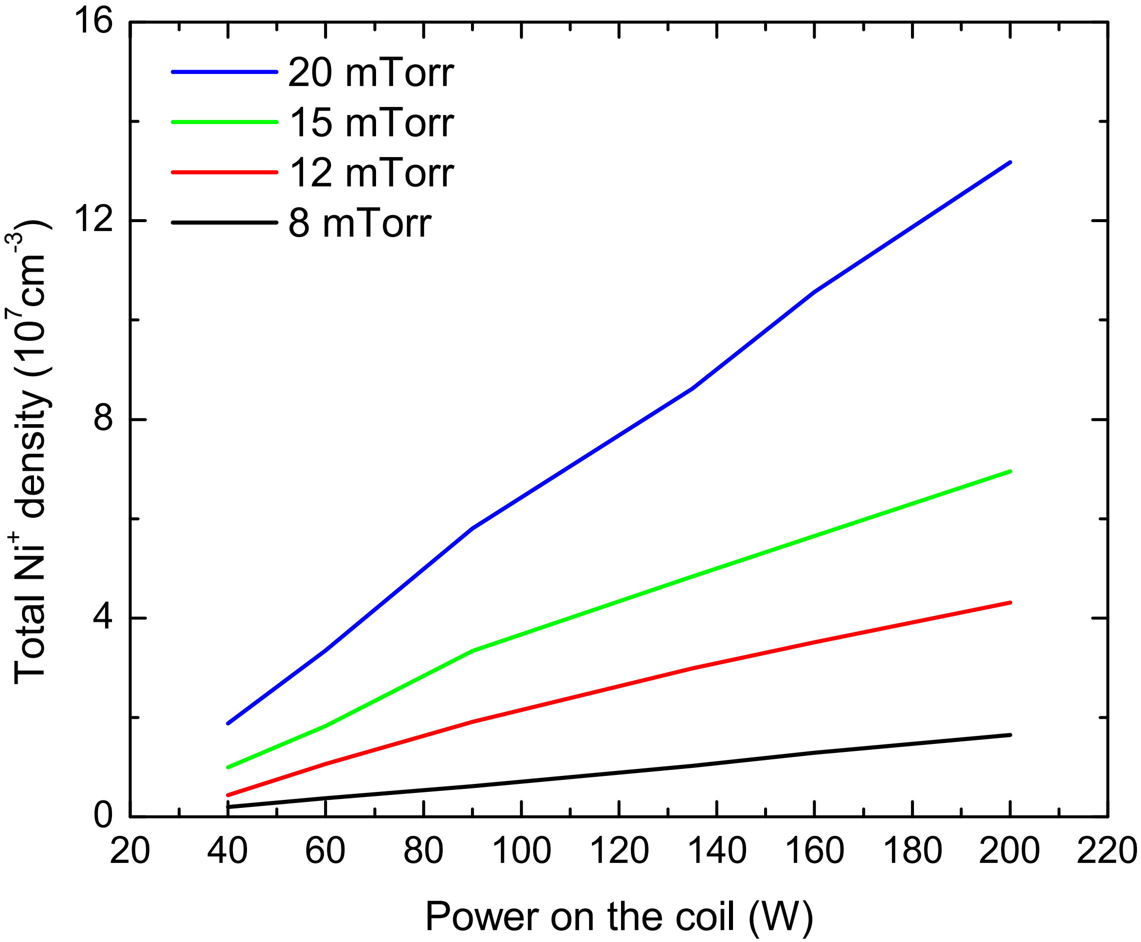
Total Ni Atom Number Densities

points: measurements; lines: model predictions



Total Ni Ion Number Densities

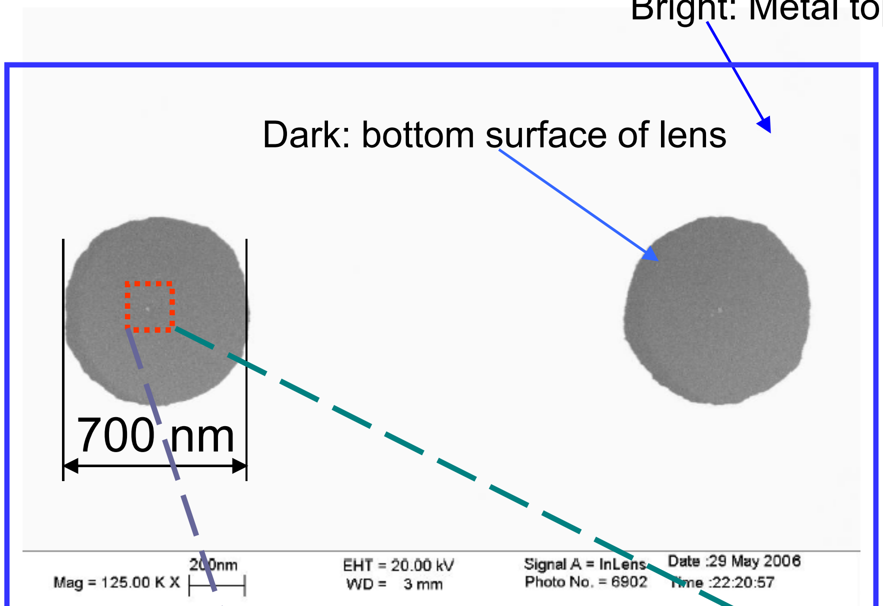
lines: model predictions

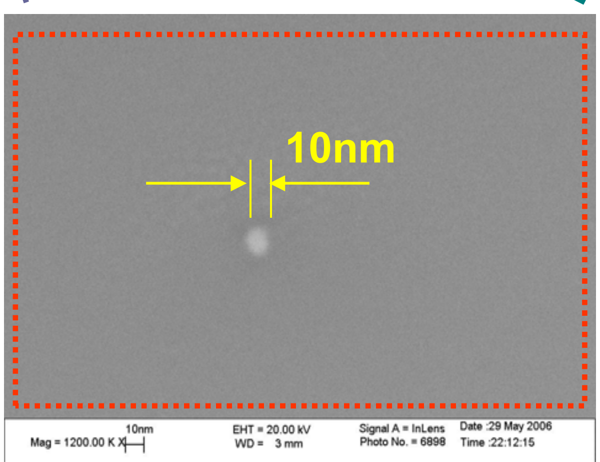


SEM images (top view) of sample after Ni deposition

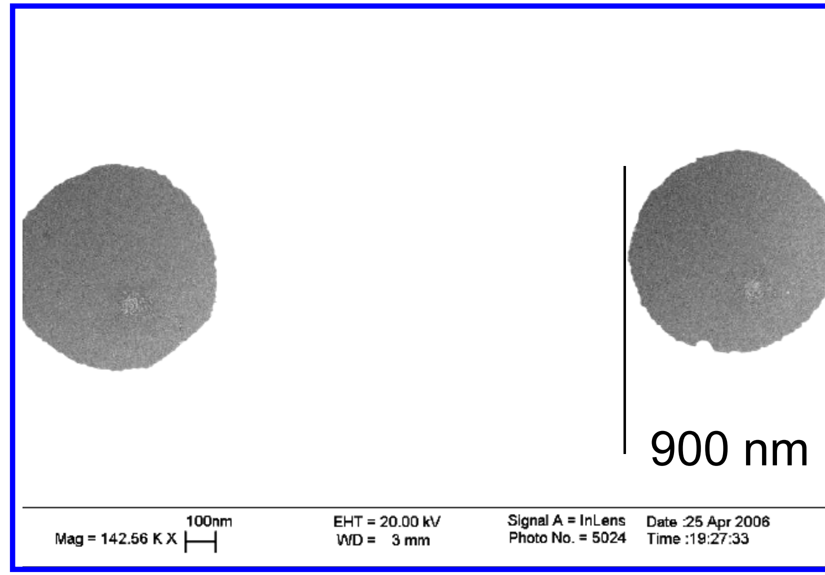
0 degree tilting

Bright: Metal top electrode



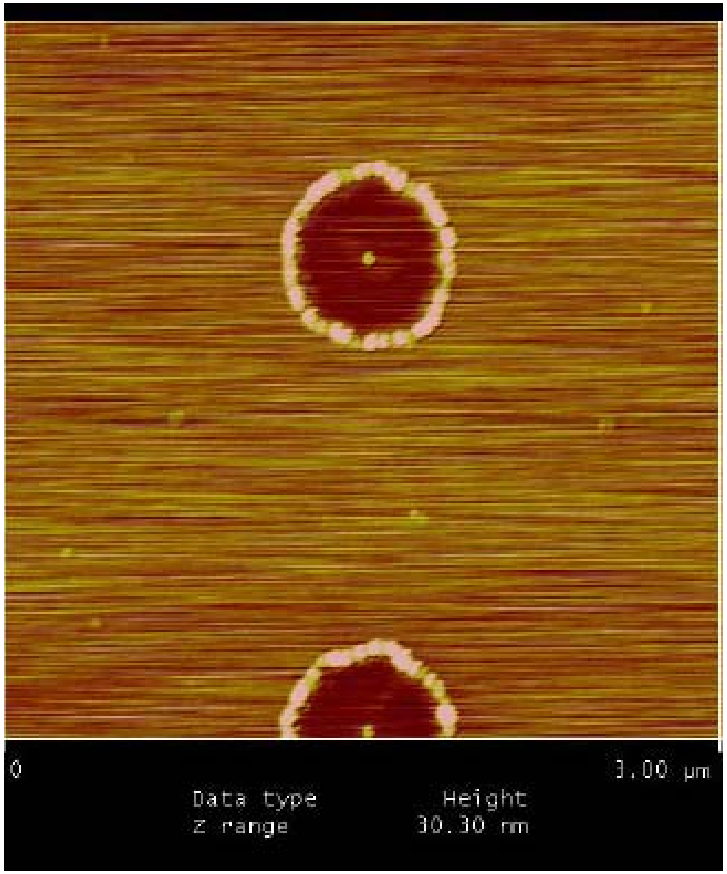


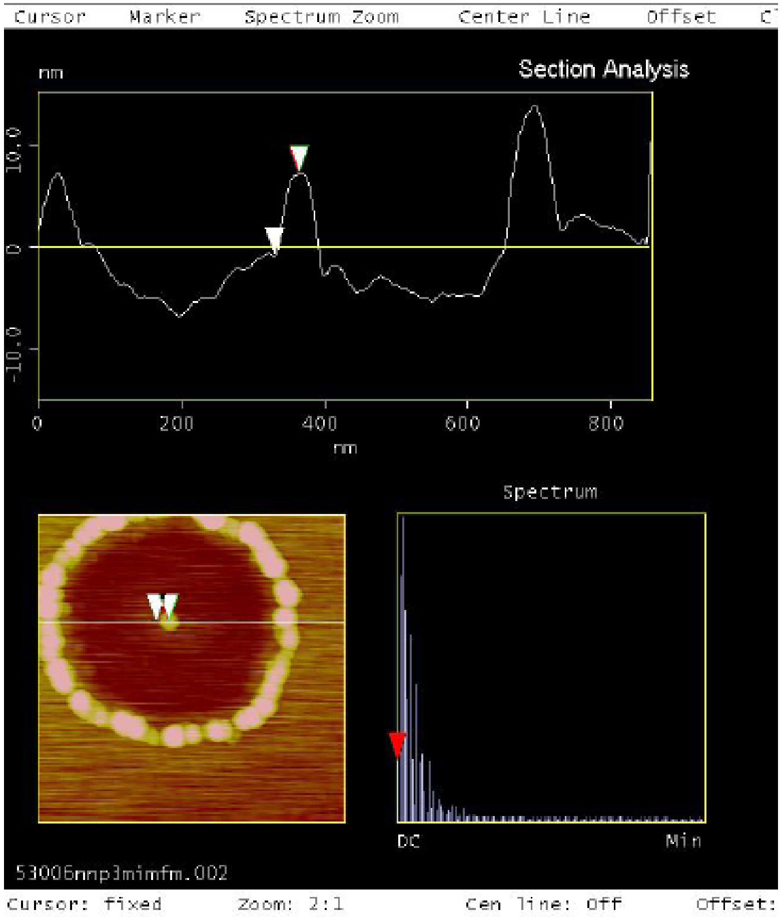
5 degree tilting(~30 nm nanodots)



The focusing ration is *70X* for the Ni nanodots!

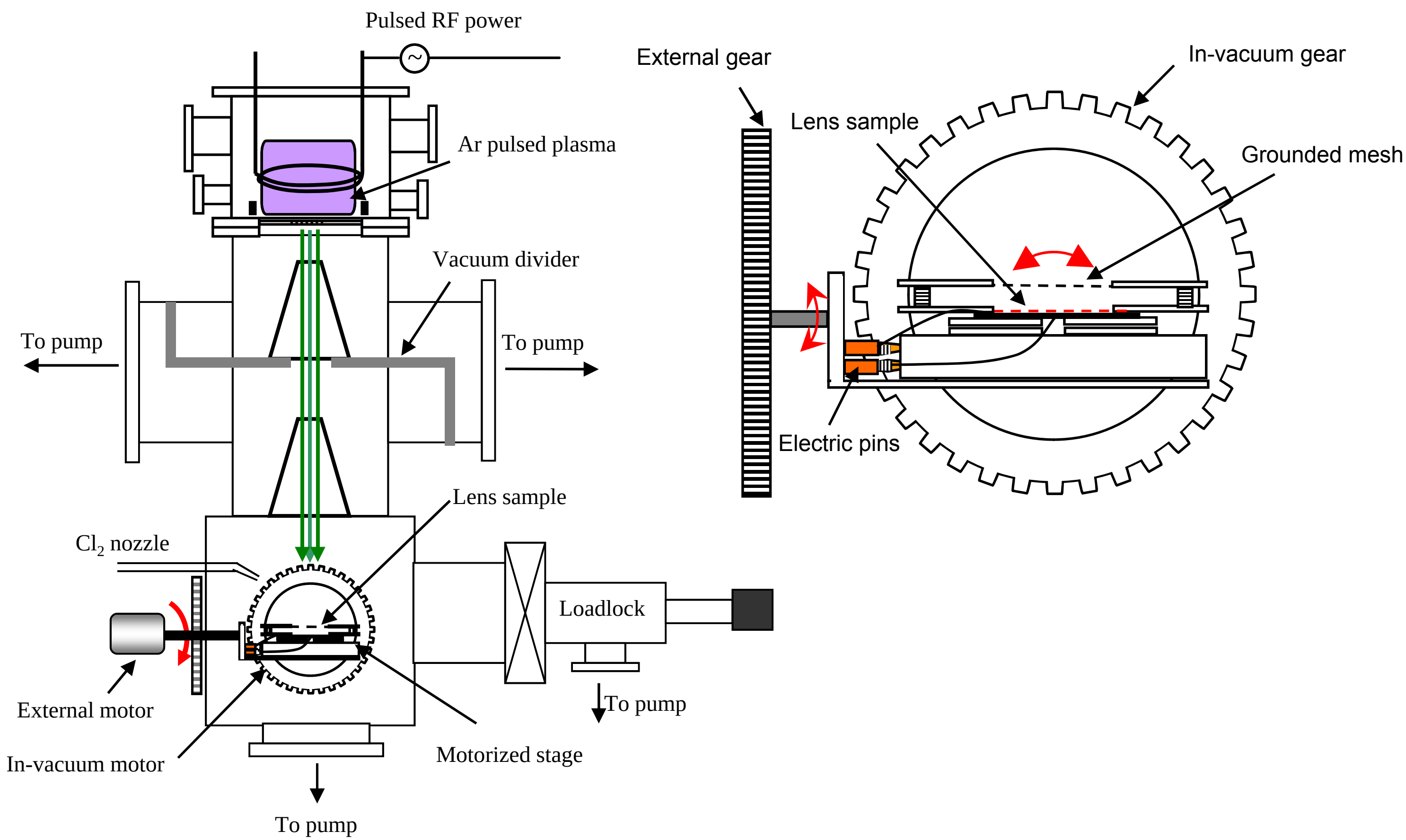
AFM images of deposited Ni nanodots





The heights of the deposited nanodots are ***5~10 nm***.

Nanopantography apparatus for continuous substrate tilting and writing

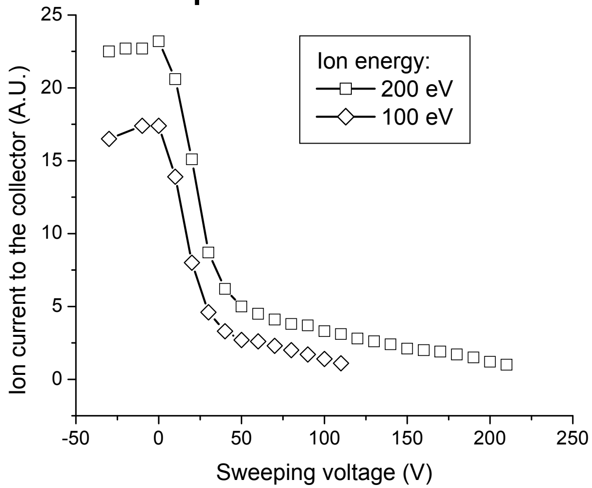


“Etching of nanopatterns in silicon by nanopantography”, L. Xu, A. Nasrullah, Z. Chen, P. Ruchhoeft, D. J. Economou and V, M. Donnelly, Appl. Phys. Letters, **92**, 013124 (2008).

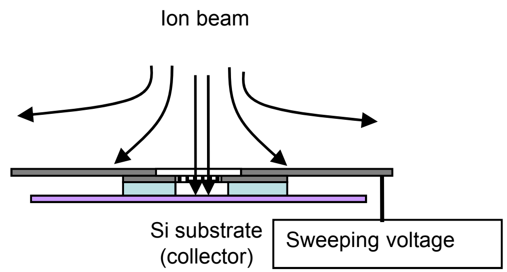
Influence of the top electrode potential of a microlens assembly on the ion current to the substrate

without grounded top mesh

: Figs. (b) and (d) are schematic illustrations of ion trajectories)

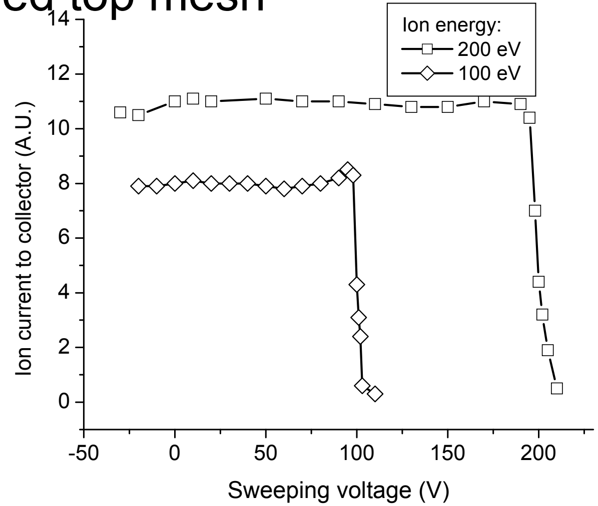


(a)

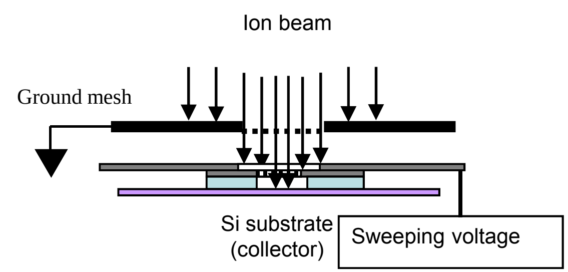


(b)

with grounded top mesh

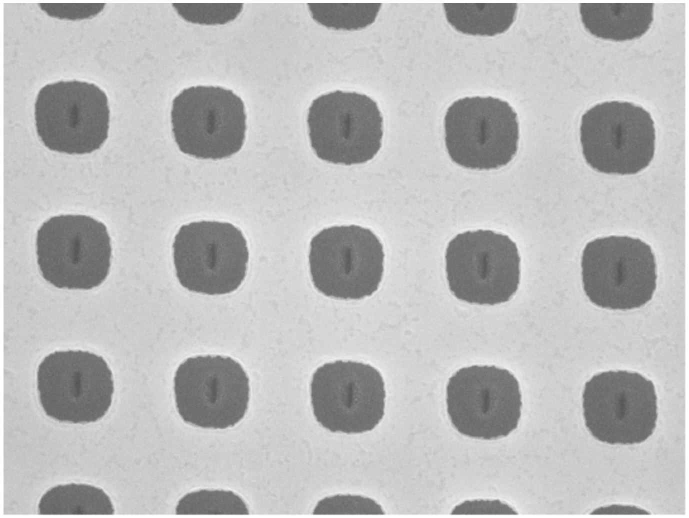


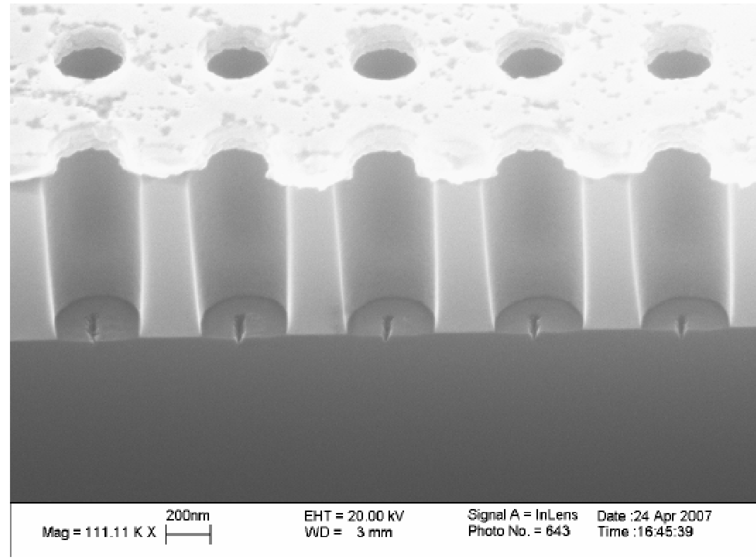
(C)

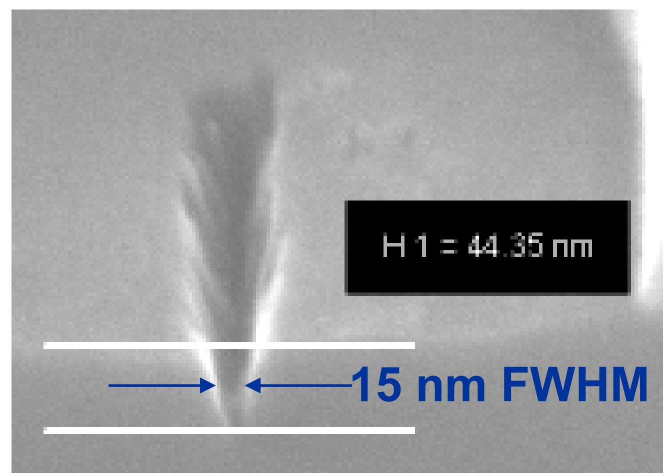


(d)

Nanopantography results: continuous writing of etched Si nano-trenches with Ar^+ / Cl_2

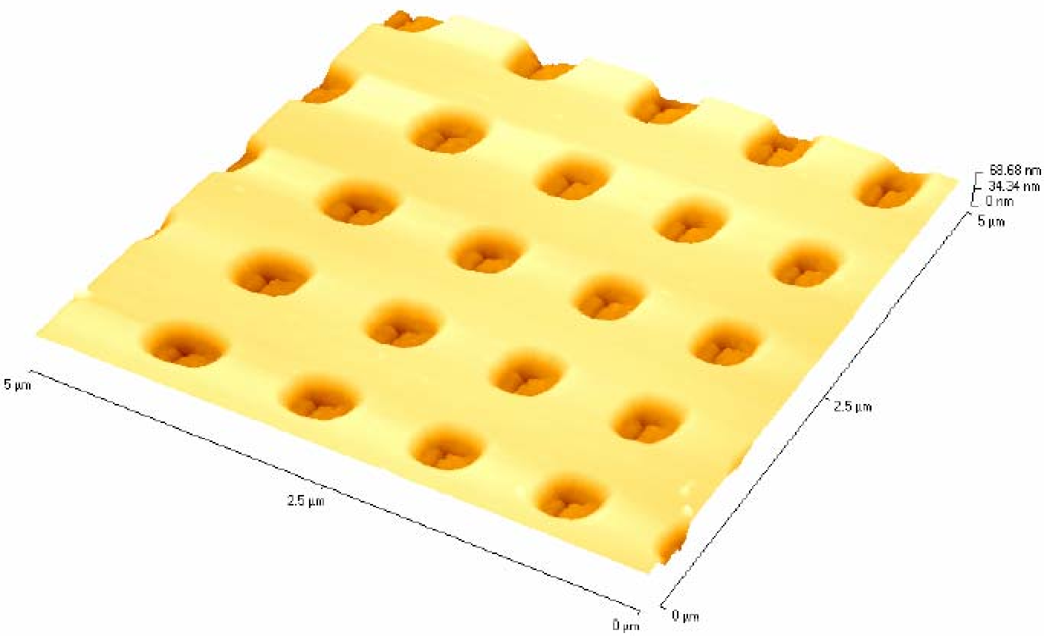


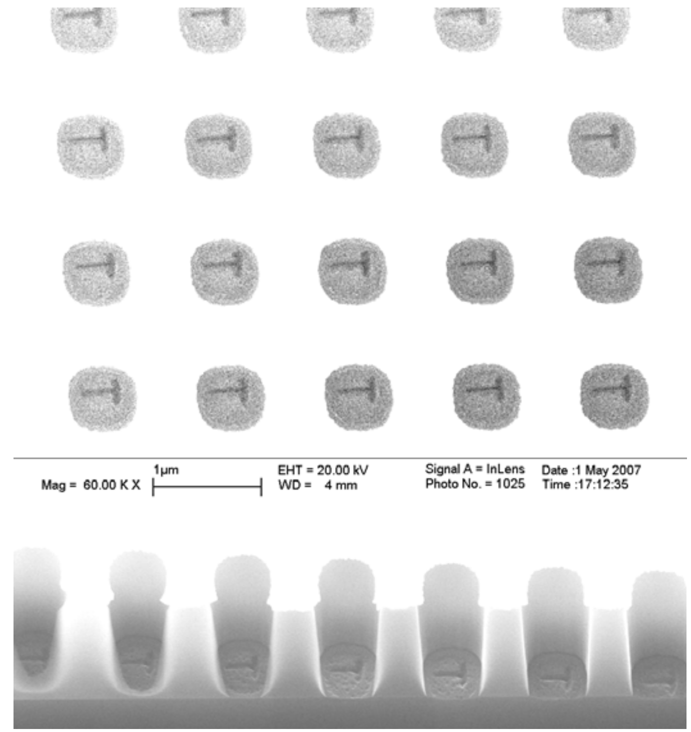




"Etching of nanopatterns in silicon by nanopantography", L. Xu, A. Nasrullah, Z. Chen, P. Ruchhoeft, D. J. Economou and V, M. Donnelly, Appl. Phys. Letters, **92**, 013124 (2008).

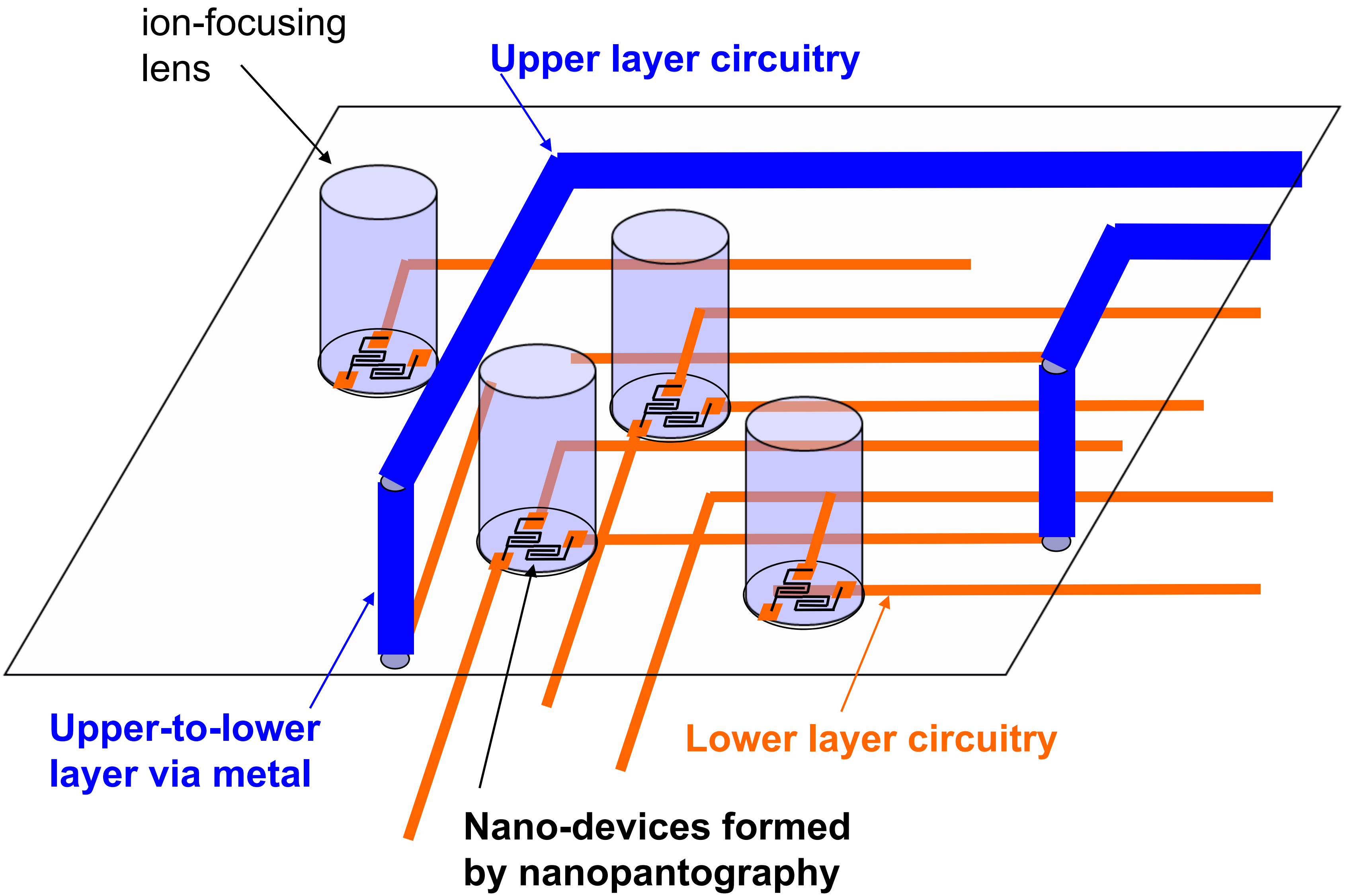
Nanopantography results: continuous writing of etched Si “nano-Ts” with Ar^+ / Cl_2





“Etching of nanopatterns in silicon by nanopantography”, L. Xu, A. Nasrullah, Z. Chen, P. Ruchhoeft, D. J. Economou and V, M. Donnelly, Appl. Phys. Letters, **92**, 013124 (2008).

Our Vision for Nanopantography



Conclusions

- We have demonstrated "Nanopantography", a new approach for fabrication of nanometer scale selected patterns over large areas.

- A nearly mono-energetic and directional Ar ion beam has been achieved for the realization of nanopantography.

- 10 nm holes were etched ~100 nm deep into Si by Ar^+ - assisted etching in Cl_2 with a reduction of ~95 x.

- 10 nm diam. Ni nanodots with heights of 5~10 nm were deposited with a Ni^+ beam

- By tilting the sample, the focal points were displaced, making possible the writing of etched nano-patterns (trenches and Ts) into Si

Acknowledgement

- *NSF (NIRT, Nanoscale Interdisciplinary Research Team Projects) and the Texas Advanced Research Program for funding.*

- *Dr. Alain Diebold and Dr. Hugo Celio, Sematech for TEM measurements.*

Outline

- Overview of nanofabrication techniques
- What is “Nanopantography”?
- A proof-of-principle experiment
- Experimental results from Nanopantography
- Summary and future work
- Acknowledgements